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The Cascadia Earthquake Early Warning System

Completion Report to the Canadian Safety and Security Program

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OCEAN NETWORKS CANADA

The Cascadia Earthquake Early Warning System Completion Report to the Canadian Safety and Security Program

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AN INITIATIVE OF University of Victoria

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Executive Summary

Ocean Networks Canada (ONC) has developed an earthquake early warning system for southwestern British Columbia that leverages existing submarine sensor networks, its world-renowned capabilities to install instrument networks both on- and offshore, and a data handling reputation for managing and processing important data volumes. Furthermore, extensive efforts have supported the integration of neighbouring seismic networks to enhance local detection capabilities, expand the system footprint, and promote operational collaborations. As the development is now virtually complete, ONC is preparing for the next important phase: a system-wide commissioning. This phase will reveal any system gaps, determine the acceptance criteria, understand and optimize operational costs by adding redundancy in key areas, and qualify the actual system's capabilities. This report will both summarize what was accomplished and articulate the the objectives of the commissioning phase of the Cascadia Earthquake Early Warning System (EEWS).

The Cascadia Earthquake Early Warning System

The three-year provincially and federally funded project has supported the installation of new sensors both along the Cascadia subduction zone (on the seafloor) and on land. This highly sophisticated and cutting-edge system is intended to provide between 30 and 90 seconds of warning of an impending ground-shaking earthquake to the main urban areas in the southwestern part of the province. The details of this important system are described in the following sections.

The Earthquake Early Warning System at a Glance

Over more than two years, ONC has installed 27 land-based and 8 seafloor stations, with a total number of approximately 90 devices (Figure 1). These stations are equipped with core components that include accelerometers, Global Navigation Satellite Systems (GNSS) and small computers to measure ground shaking, provide accurate geospatial positioning and perform comprehensive data processing and system analyses, respectively. The land-based subsystems comprising joint Natural Resources Canada (Natural Resources Canada) and ONC stations and components, and also include ONC-only managed sites. Stations vary largely in their power and communications requirements as these are dependent on the site location both geographically and within the system topology. Additionally, ancillary equipment also varies on a site-by-site basis where need is defined by sensors, hardware, managing authorities, power consumption, communication bandwidth access, environmental factors, geographical location, land-owners, elevation, site accessibility and systems hardware to name a few.

ONC successfully developed an EEW system able to achieve operational capabilities by providing notification to stakeholders in southwestern BC about offshore earthquake events originating in or near the Cascadia subduction zone. The initial agreement included the expected acquisition and installation of 8 offshore and 36 land-based seismic and deformation sensors around Vancouver Island. Impressively, ONC, in coordination with Natural Resources Canada, was able to not only install the underwater sensors, but also successfully integrated 51 in-land instruments (seismic+GNSS) spanning both Vancouver Island and southern mainland coastal British Columbia. Data sharing capabilities have been established and implemented with both Natural Resources Canada and the Pacific Northwest Seismic Network (Pacific Northwest Seismic Network), in addition to successful end-user testing with a variety of beta testers. Comprehensive software capable of seismic and deformation data analysis has been1 developed to both accurately detect and deliver reliable notifications to potential alerting authorities.

During late 2018, several seismic events were detected with an adequate level of precision. A noteworthy event occurred on October 22, 2018, where the EEWS predicted an estimated level of magnitude later confirmed to be very accurate. The ONC EEWS would have provided a 68 second advance notice to stakeholders before potential ground shaking. Considering this encouraging first success, and our knowledge of the system, ONC is confident that following full system commissioning, the EEWS will be adopted by many stakeholders who will use it to mitigate the impact of earthquakes on property and life.

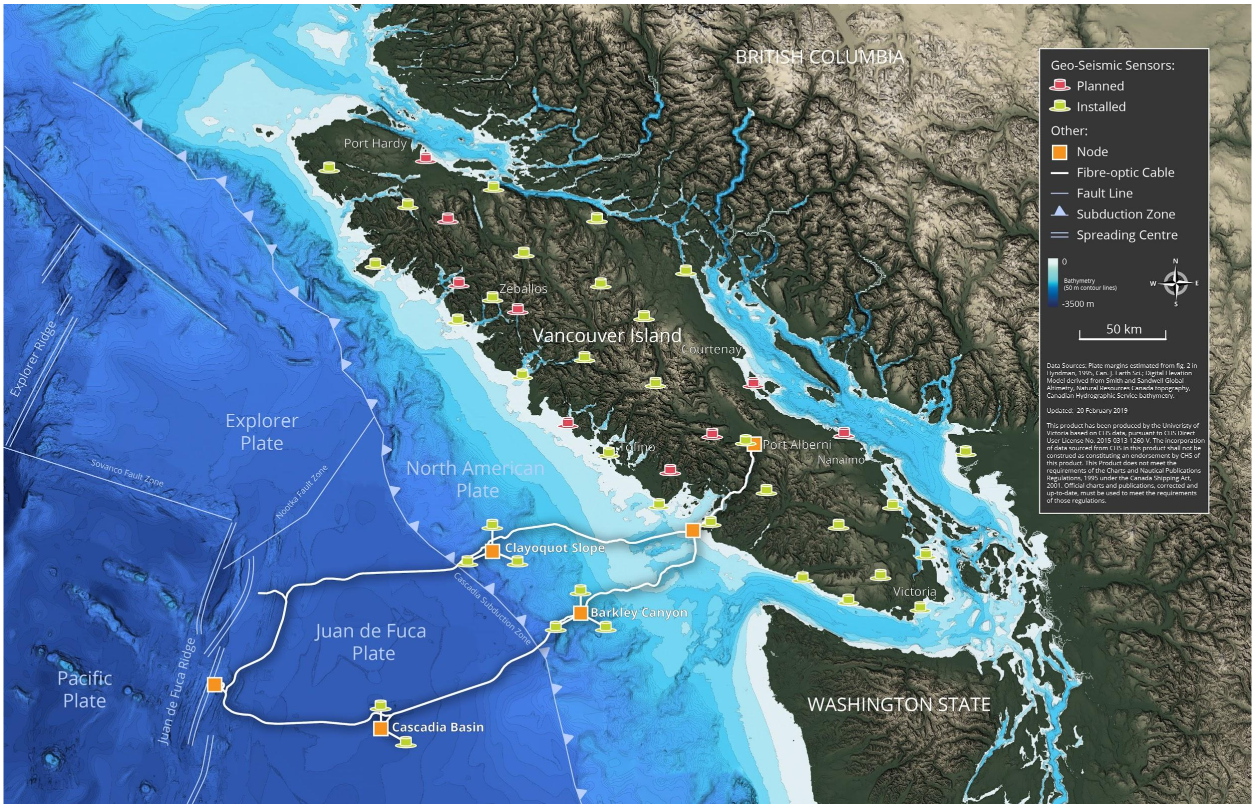


Figure 1: A high-level view of the current EEWS station locations and installation status, where a green symbol indicates a fully installed station and a red symbol indicates a station that is planned for installation in the very near future.

Station Summary

ONC and Natural Resources Canada integrated their networks for select stations where sensors provided by either party contribute to the overall system (Figure 2). The details of this integration are covered in later sections, but a high level summary of currently integrated sensors is outlined here. This network integration has three cases, where ONC owns all, some or none of the instrumentation installed at a site. For the latter two cases, ONC has contributed ancillary hardware, financial resources, equipment and materials, staff labour, logistics and planning support, transport and shipping, storage and various other support. Regardless of instrument ownership, it is important to note the significant contribution from both parties and the coordinated, concerted effort that was necessary to complete all physical network upgrades and sensor integration.

For a closer look at the geographical location where each sensor is installed, refer to the KML file provided with this report, which includes a GIS map layer identifying the specific locations of each instrument. These details are also provided as a list (Table 1) where the term “seismic” refers to either an accelerometer or a tiltmeter for only the underwater stations, and includes the current instrument integration status to-date. An ONC owned station is defined as a station that has been solely installed and operated by ONC. ONC-Natural Resources Canada jointly owned stations are composed of both ONC and Natural Resources Canada owned instrumentation and equipment, where both parties contributed to the station installation, completion and commissioning. Natural Resources Canada owned stations utilize Natural Resources Canada owned GNSS and

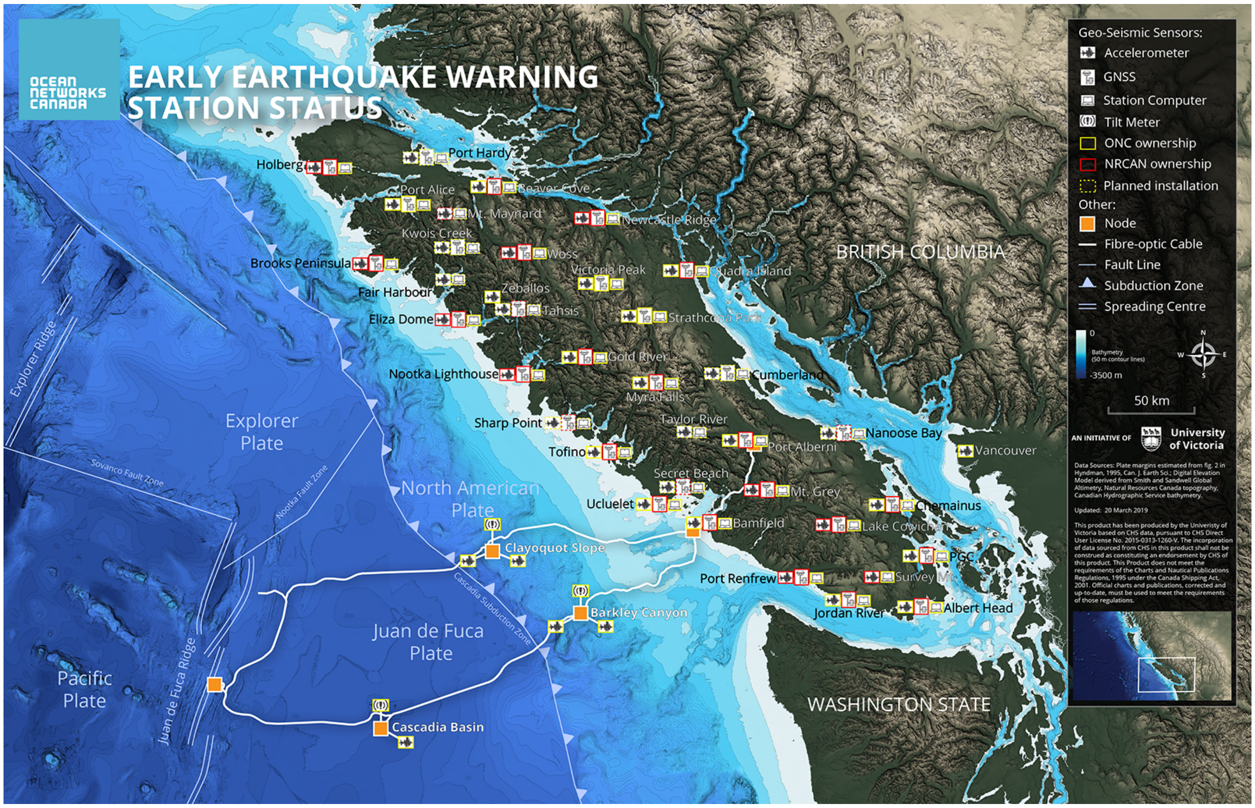


Figure 2. A detailed view of the current status of EEWS station components, where instruments are indicated by a corresponding symbol identified in the legend at the top right hand corner. Icons are bordered by either a yellow (ONC-owned) or red (Natural Resources Canada-owned) box to indicate ownership. A solid line represents a fully installed instrument, whereas a dashed line indicates a planned installation.

accelerometers, while ONC contributed largely in the form of ancillary equipment, staff and financial resources, materials, support, etc.

The specific details of each individual station integrated into the EEWS is discussed in further detail in following sections. And Appendix I includes a description the entire physical EEWS system and its components, including a complete inventory of the physical assets.

Table 1. Current EEWS sensor deployment status by ownership and deployment status. An "x" shows installation status.

Name/Location (Land Based)		Seismic	GNSS	Station Status
ONC Owned Stations				
1	Port Alice	x	x	Online streaming data for testing
2	Strathcona Park	x	x	Online streaming data for testing
3	Vancouver	x		Online streaming data for testing
4	Victoria Peak	x	x	Online streaming data for testing
5	Zeballos	x		Online streaming data for testing

Name/Location (Land Based)		Seismic	GNSS	Station Status
ONC-Natural Resources Canada Jointly Owned Stations				
6	Albert Head	x	x	Online streaming data for testing
7	Bamfield	x	x	Online streaming data for testing
8	Beaver Cove	x	x	Online streaming data for testing
9	Chemainus	x	x	Online streaming data for testing
10	Gold River	x	x	Online streaming data for testing
11	Jordan River	x	x	Installed, not streaming data
12	Myra Falls	x	x	Online streaming data for testing
13	Sidney	x	x	Pending SSC* security audit
14	Port Alberni	x	x	Online streaming data for testing
15	Quadra Island	x	x	Online streaming data for testing
16	Tofino	x	x	Online streaming data for testing
17	Ucluelet	x	x	Online streaming data for testing
Natural Resources Canada owned stations				
18	Brooks Peninsula	x	x	Online streaming data for testing
19	Eliza Dome	x	x	Online streaming data for testing
20	Holberg	x	x	Installed, not streaming data
21	Lake Cowichan	x	x	Online streaming data for testing
22	Mount Grey	x	x	Online streaming data for testing
23	Newcastle Ridge	x	x	Online streaming data for testing
24	Nootka Lighthouse	x	x	Online streaming data for testing
25	Port Renfrew	x	x	Online streaming data for testing
26	Survey Mountain	x		Pending Shared Services Canada security audit
27	Woss	x	x	Online streaming data for testing
Subtotal		**27**	**24**	

Name/Location (Land Based)		Seismic	GNSS	Station Status
ONC Owned Planned Stations				
28	Cumberland	Planned	Planned	To be integrated
29	Kwois Creek	Planned	Planned	To be integrated
30	Port Hardy	Planned	Planned	To be integrated
31	Secret Beach	Planned	Planned	To be integrated
ONC-Natural Resources Canada Jointly Owned Planned Stations				
32	Fair Harbour	Planned		To be integrated
33	Mount Maynard	Planned		To be integrated
34	Nanoose Bay	Planned	Planned	To be integrated
35	Sharp Point	Planned	Planned	To be integrated
36	Tahsis	Planned	Planned	To be integrated
37	Taylor River	Planned		To be integrated
Natural Resources Canada Owned Planned Stations				
38	Mount Maynard	Planned		To be integrated
Subtotal		**10**	**7**	
Name/Location (Ocean Based)		**Seismic**	**GNSS**	**Station Status**
39	Barkley Canyon Mideast	x	N/A	Online streaming data for testing
40	Barkley Canyon Node	x	N/A	Online streaming data for testing
41	Barkley Canyon Upper	x	N/A	Online streaming data for testing
42	Cascadia Basin CORK ODP 1027C	x	N/A	Online streaming data for testing
43	Cascadia Basin CORK ODP 1027C	x	N/A	Online streaming data for testing
44	Clayoquot Slope - Bullseye	x	N/A	Online streaming data for testing
45	Clayoquot Slope - Bullseye	x	N/A	Online streaming data for testing
46	Clayoquot Slope ODP 1364A	x	N/A	Online streaming data for testing
Subtotal		**8**	**0**	
Total		**46**	**31**	

ONC Sensor Integration

ONC manages and operates a number of stations independently of other externally owned networks. These sites span both the ocean floor and southern coastal British Columbia. The instruments and station components deployed here are entirely owned and operated by ONC. Furthermore, ONC can verify the rigorous testing procedures that were practiced from asset receipt to deployment. This section details the ONC-owned portion of the Cascadia EEWS. Other networks of sensors data are integrated into the EEWS but are not operated or maintained by ONC.

Ocean-based ONC-owned Instrument Network

ONC manages an important asset that offers unique benefits to an Earthquake Early Warning system and sets it apart from any currently operational networks worldwide. This pre-existing research infrastructure located on the ocean floor off of the west coast of Vancouver Island, and in close proximity to important fault lines, is the primary reason ONC was selected to implement an Earthquake Early Warning System for southern British Columbia. The NEPTUNE underwater offshore observatory spans the Cascadia subduction zone (CSZ) and offers a cost-effective expansion solution, that makes it the optimal place to install seismic sensors on and at either side of the CSZ. Utilizing this subsea facility adds as many as 10 additional seconds of warning time to Southern coastal British Columbia in the event that a rupture originates in the vicinity of the underwater array. The earthquake early warning component of this infrastructure will be discussed in more detail below.

ONC Managed Stations

ONC completed the installations of instruments for the EEW system at Barkley Canyon, Cascadia Basin and Clayoquot Slope (Table 2).

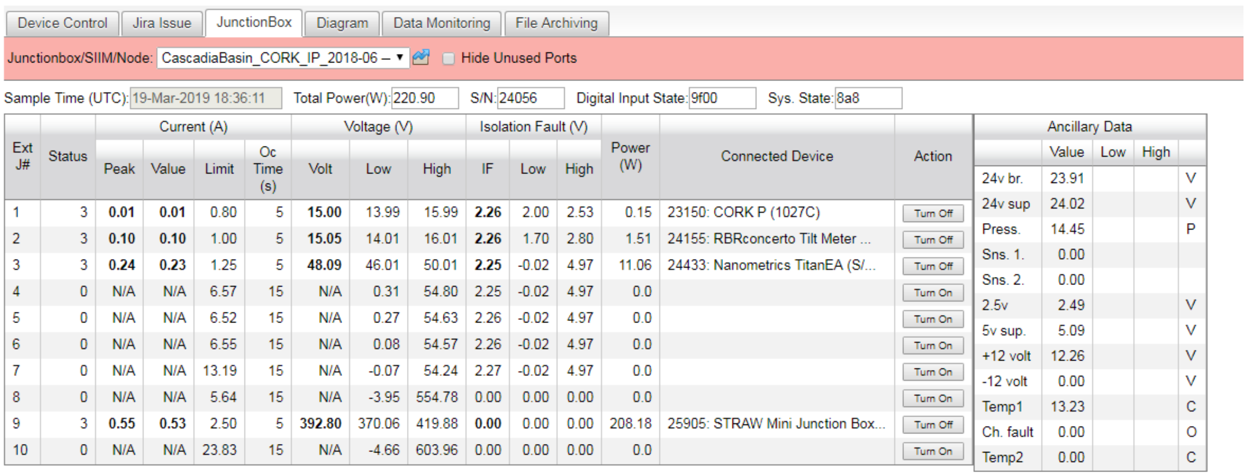
Table 2. A summary of the type of instrument and its corresponding location deployed on the ocean floor. All stations

Location (IRIS Station Code)		Instrument Model and Serial Number
1	Barkley Canyon Mideast (BACME.W1)	Nanometrics TitanEA (S/N 000143)
2	Barkley Canyon Node (BACND.Z1)	RBRconcerto Tilt Meter ACC.BPR 63056
3	Barkley Canyon Upper Slope (NCBC.W1)	Nanometrics TitanEA (S/N 000646)
4	Cascadia Basin CORK ODP 1027C (CBC27.Z1)	RBRconcerto Tilt Meter ACC.BPR 63057
5	Cascadia Basin CORK ODP 1027C (CBC27.W1)	Nanometrics TitanEA (S/N 000788)
6	Clayoquot Slope - Bullseye (NC89.W1)	Nanometrics TitanEA (S/N 000647)
7	Clayoquot Slope ODP 1364A (CQS64.W1)	Nanometrics TitanEA (S/N 000787)
8	Clayoquot Slope - Bullseye (NC89.Z1)	RBRconcerto Tilt Meter ACC.BPR 63055

The Nanometrics Titan EA accelerometers and RBR Tilt Meters (model ACC.BPR -- also containing an accelerometer on top of orientation sensors) are connected to the network via underwater wet-mateable ports to a junction box. Falmat cables of 25-45m are typically used for this connection. For the tilt meters, the port is configured to provide Ethernet communications and 15 Volt power supply to the instrument. For the accelerometers, the port is configured to provide Ethernet communications and a 48 Volt power supply.

As these data types are considered sensitive by the defence departments, middleware directly communicating with these sensors is executed on a defence department machine at the shore station using a separate virtual network. To obtain the derived EEW parametric data, the ONC driver then communicates with this machine via a port defined for each instrument.

Through junction box telemetry, ONC monitors and archives current, voltage, isolation fault and power to each port at 1Hz (Figure 3). Each port can be set with limits to produce alerts for response by system operators.


Device Control | Jira Issue | JunctionBox | Diagram | Data Monitoring | File Archiving

Junctionbox/SIIM/Node: CascadiaBasin_CORK_IP_2018-06 – Hide Unused Ports

Sample Time (UTC): 19-Mar-2019 18:36:11 Total Power(W): 220.90 S/N: 24056 Digital Input State: 9f00 Sys. State: 8a8

Ext J#	Status	Current (A)				Voltage (V)			Isolation Fault (V)			Power (W)	Connected Device	Action
		Peak	Value	Limit	Oc Time (s)	Volt	Low	High	IF	Low	High			
1	3	**0.01**	**0.01**	0.80	5	**15.00**	13.99	15.99	**2.26**	2.00	2.53	0.15	23150: CORK P (1027C)	Turn Off
2	3	**0.10**	**0.10**	1.00	5	**15.05**	14.01	16.01	**2.26**	1.70	2.80	1.51	24155: RBRconcerto Tilt Meter ...	Turn Off
3	3	**0.24**	**0.23**	1.25	5	**48.09**	46.01	50.01	**2.25**	-0.02	4.97	11.06	24433: Nanometrics TitanEA (S/...	Turn Off
4	0	N/A	N/A	6.57	15	N/A	0.31	54.80	2.25	-0.02	4.97	0.0		Turn On
5	0	N/A	N/A	6.52	15	N/A	0.27	54.63	2.26	-0.02	4.97	0.0		Turn On
6	0	N/A	N/A	6.55	15	N/A	0.08	54.57	2.26	-0.02	4.97	0.0		Turn On
7	0	N/A	N/A	13.19	15	N/A	-0.07	54.24	2.27	-0.02	4.97	0.0		Turn On
8	0	N/A	N/A	5.64	15	N/A	-3.95	554.78	0.00	0.00	0.00	0.0		Turn On
9	3	**0.55**	**0.53**	2.50	5	**392.80**	370.06	419.88	**0.00**	0.00	0.00	208.18	25905: STRAW Mini Junction Box...	Turn Off
10	0	N/A	N/A	23.83	15	N/A	-4.66	603.96	0.00	0.00	0.00	0.0		Turn On

Ancillary Data	Value	Low	High	
24v br.	23.91			V
24v sup	24.02			V
Press.	14.45			P
Sns. 1.	0.00			
Sns. 2.	0.00			
2.5v	2.49			V
5v sup.	5.09			V
+12 volt	12.26			V
-12 volt	0.00			V
Temp1	13.23			C
Ch. fault	0.00			O
Temp2	0.00			C

Figure 3. A screenshot of the Junction Box View tool for controlling and monitoring power to instruments.

Pre-Deployment testing framework for ONC-owned instrumentation

Pre deployment data validation is a key operational process to ensure a functional instrument producing scientifically accurate data is deployed into the field. This process is critical to ensure the integrity of the ONC data delivered to the public and the science community.

The accelerometers are setup for data validation testing in a quiet underground facility (seismic vault) at the Pacific Geoscience Centre. The data are recorded over a period of one week for spectral analysis and instrument sensitivity verification. Comparison to seismic data from another instrument that is co-located in the seismic vault and owned by Natural Resources Canada/Canadian Hazard Information System ensures the data quality of the tested instrument. Once these tests are done, the instrument is transferred to the Marine Technology Centre to be connected to the Data Acquisition Framework testing environment in Oceans 2.0, ONC's integrated data management system. In this step, the derived parameters that are essential input to the EEWS Software suite are verified and compared to existing test data available in Oceans 2.0. The RBR tiltmeter data are recorded from testing the instruments performance in an outdoor pool at the Marine Technology Centre facility. The instrument is connected to the Data Acquisition Framework testing environment in Oceans 2.0 to ensure the data quality of the required parameters for the EEWS software suite.

Integration of ONC-owned Instrument Data into Oceans 2.0

The primary underwater data integrated into the EEW system are the derived parameters that are computed by middleware at the shore station in Port Alberni. These parameters are:

- JMA Intensity Amplitude
- Maximum Peak Displacement Amplitude
- Maximum Predominant Period
- Peak Displacement Amplitude
- Predominant Period
- P-wave Arrival Time
- P-wave Detection Ratio
- S-wave Arrival Time

- S-wave Detection Ratio

An Oceans 2.0 driver connects to this middleware to receive the data streams. Upon driver start up, the version of the middleware is sent and archived as provenance information. Currently, the JMA Intensity Amplitude reports every 1Hz and serves as heartbeat, while other parameters are transmitted only in the case of an event. The computed parameters are parsed and archived in the database in near real-time.

The raw data streams for both instruments are made available through the Incorporated Research Institutions for Seismology (IRIS) after being downsampled to adhere to military restrictions. Raw data files for the tiltmeter are also assembled in daily file for archival into Oceans 2.0. The current data stream status for each instrument is shown in Table 1.

Subsea Maintenance

ONC regularly conducts maintenance expeditions for the NEPTUNE observatory, usually two times each year using ocean-going ships and remotely operated vehicles. Six expeditions have contributed to the installation of EEW instruments since 2016 (Table 3).

Table 3. Sub-sea maintenance expeditions and activities relevant for EEW system.

Dates	Ship	Remotely Operated Vehicle	Relevant Activities
2016-06-13 to 2016-06-26	R/V Sikuliaq	Jason II	Completed caisson installation for Titan EA at Barkley Canyon Mid-East (dive J0885) Placed Titan EA on seafloor at Clayoquot Slope CORK (dive J0898), pending caisson installation in later expedition
2017-04-28 to 2017-05-29	CCGS John P. Tully	Odysseus	Placed Titan EA at Clayoquot Slope Bulls-eye (dive OY007), pending caisson installation in later expedition
2017-06-06 to 2017-06-27	E/V Nautilus	Hercules	Installed Tilt Meters at Clayoquot Slope (dive H1579); Completed caisson installation for Titan EA at Clayoquot Slope Bullseye (H1579); Placed caisson at Clayoquot Slope CORK station (dive H1578), Titan EA pending caisson installation in later expedition
2018-06-10 to 2018-07-02	CCGS John P. Tully	ROPOS	Installed Tilt Meters at Barkley Node (dive R2076) and Cascadia Basin (dive R2079) Placed Titan EA on seafloor at Cascadia Basin (dive R2079) and at Barkley Upper Slope (R2089), pending full caisson installation in later expedition
2018-07-21 to 2018-08-05	E/V Nautilus	Hercules	Completed caisson installation for Titan EA at Cascadia Basin (dive H1692) and Clayoquot Slope (dive H1698), and Barkley Upper Slope (dive H1701); Recovered Titan EA from Clayoquot Slope CORK due to failed internal flash card (dive H1698).
2019-01-27 to 2019-01-30	CS Cable Innovator	ST-205	Inspected Barkley Upper Slope site for impacts from a trawling event in 2018-11. The Titan EA cable had no apparent disruption to its cable burial, although the actual instrument was not inspected.

Each installation is described in detailed instructions in a dive plan used to guide ship personnel (e.g., remotely operated vehicle pilots, ONC dive chief) and shore support staff.

An example excerpt from a dive plan for a tiltmeter installation at Barkley Node is as follows:

```
1. Request System Operations to confirm power off Barkley Canyon Node JB-09 Port
   J2 and that port is configured to 15V.
2. Tiltmeter connector already attached to JB-09 Port J2 .
3. ROV release instrument cable (ExtensionID: 819) by removing ring on horns and
   ROV remove bungie holding instrument in place in PVC tube.
4. Request System Operations to power on Barkley Canyon Node JB-09 Port J2.
5. Shore will attempt to communicate with the instrument
6. In the PVC tube on the platform, perform a 1-g calibration by executing the
   following steps:
      a. Position the ROV steadily on the seafloor;
      b. Let the instrument record for approx. one minute in the horizontal
         position (ideally with X or Y vertical);
      c. then rotate 90 degrees to have Y or X vertical and record for another
         minute.
7. ROV remove the instrument from the tube by the handle.
8. ROV transit in a west direction  about 5 -7 meters watching green cable clears
   horns.
9. ROV align the instrument vertically (perpendicular to seabed).  Perfectly
   vertical is desired, but the the insertion should follow a linear trajectory to
   optimize the quality of the contact of the instrument to the sediment.
10. If a second insertion attempt is needed, it should be done several meters away
   from the first.
11. Push the instrument into the seafloor, minimizing lateral excursions to
   maximize quality of accelerometer/sediment coupling.  Ensure that the top of
   accelerometer is flush with or below seafloor to avoid current-induced noise
12. Take a final heading of the instrument and photograph the bullseye level if
   still visible.
13. ROV confirm cable within three meters of the instrument is flush with the
   seafloor.
14. If necessary use cable staple to secure cable to floor.
```

And the actual deployment of a tiltmeter at Barkley Node can be viewed using the Oceans 2.0 SeaTube interface with remotely operated vehicle video via the following link:

https://data.oceannetworks.ca/SeaTube?resourceTypeId=1000&resourceId=1001&diveId=1770&time=2018-06-22T01:57:38.000Z

Step 11 in the dive plan (Figure 4) shows the remotely operated vehicle, via shipboard pilot control, pushing an RBR tilt meter into the sediment at the Barkley Node location.

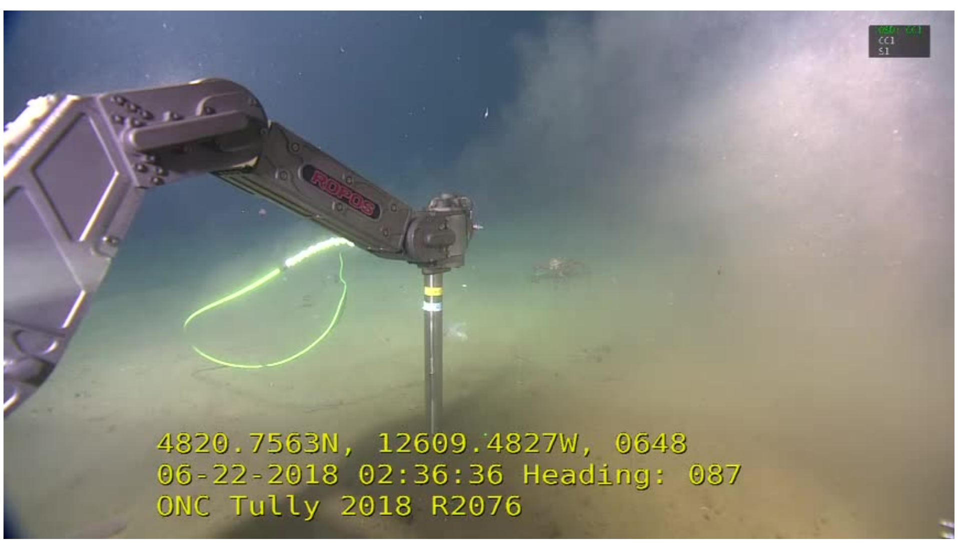


Figure 4. An RBR Tiltmeter is installed at the Barkley Node station.

Similarly, an example excerpt from a dive plan for a Nanometrics TitanEA installation at Clayoquot Slope includes the following steps:

Note: Handle the TitanEA with care. Do not shake it like a Polaroid or drop the Titan during installation

1. Release dual pull pins-bungie TitanEA connector and cable (ExtensionID: 801) and transit back to JB-08
2. Remove parking position from TitanEA connector and stow on ROV
3. Connect TitanEA connector to JB-08 Port J7
4. Request System Operations to power ON CORK 1326A JB-08 Port J7
5. Have Shore confirm that TitanAE is functional
6. Transit to TitanEA caisson location
7. ROV dredge used to remove sediments from the caisson
8. Align ROV on caisson sighting North
9. Place marker on the north side of the caisson to provide a N/S orientation through the midpoint of the caisson
10. Stop dredging when level is below 2 inches to 0 (titan is 26” high).
11. Request System Operations to power OFF CORK 1326A JB-08 Port J7
12. Place two bead bag contents into now empty caisson.
13. Empty bags place off work area for later collection.
14. Move TitanEA from temporary location to caisson
15. Carefully deploy the TitanEA housing centrally into the caisson such that the north marking on the TitanEA housing is aligned with the previously deployed north marker. The cable from the TitanEA housing should ideally be flat to the seafloor crossing the caisson lip. The handle of the TitanEA housing must be below the top of the caisson
16. Check the TitanEA housing orientation along the N-S axis. To do this have the ROV orient north over the caisson and look down at the north marking of the TitanEA housing to determine the TitanEA housing’s orientation relative to the ROV. Gently twist on the TitanEA housing handle to adjust its orientation if need be. Take several screen captures looking down at the TitanEA housing
17. With TitanEA housing oriented, place the bullseye level on top of TitanEA housing to determine levelness. There is a round area at the top of the TitanEA housing for a bullseye level to be placed during deployment to check the levelness of the housing. Make sure the level is sitting correctly on top of the Titan. There is a bolt which protrudes from the back side of the level which must be positioned such that the level sits flat.
18. Nudge TitanEA housing handle to adjust levelness as need be and re-check orientation along N-S axis if necessary.
19. Once level and orientation are as good as possible (orientation is the more important of the two; out-of-level can be compensated for), fill the caisson with glass beads. This will require the ROV to fly to the package, retrieve a glass bead bag, fly back to caisson, puncture the glass bead bag, pour the contents in the caisson, leave the empty glass bead bag somewhere it can be retrieved later, and repeat.
20. Check the bullseye level every couple of bags to confirm the TitanEA is staying relatively level.
21. TBOS is on porch to clear beads from top of level to enable sight of level.
22. When the level of glass beads gets near to the bullseye level, retrieve the bullseye level from the top of the TitanEA housing and place bullseye level in porch bio box.
23. Continue to pour glass beads until the TitanEA housing and caisson are buried. Remove the north marker and place in biobox and leave the seafloor as smooth as possible so that there are no obstructions to the bottom current
24. Record final location of the buried TitanEA
25. Retrieve rebar staples and return to caisson
26. Use rebar staples to secure cable leaving the caisson to the sediment up to ~5m away so that no part of the cable can be moved by the bottom current
27. Bury the cable with remaining glass beads
28. Cleanup site (retrieve the caisson steel lid, any empty glass bead bags, and any remaining full glass bead bags and stage for later future.
29. Take pictures of the buried TitanEA housing and its cable
30. Request System Operations to power ON CORK 1364A JB-08 Port J7
31. Request shore support checks functionality of the TitanEA

The actual accelerometer deployment at Clayoquot Slope can be seen in Oceans 2.0 SeaTube interface with ROV video via the following link:

https://data.oceannetworks.ca/SeaTube?resourceTypeId=1000&resourceId=23543&diveId=1950&time=2018-07-29T22:04:53.000Z

Step 15 in the dive plan (Figure 5) shows the remotely operated vehicle, via shipboard pilot control, inserting the Titan EA accelerometer into the caisson.

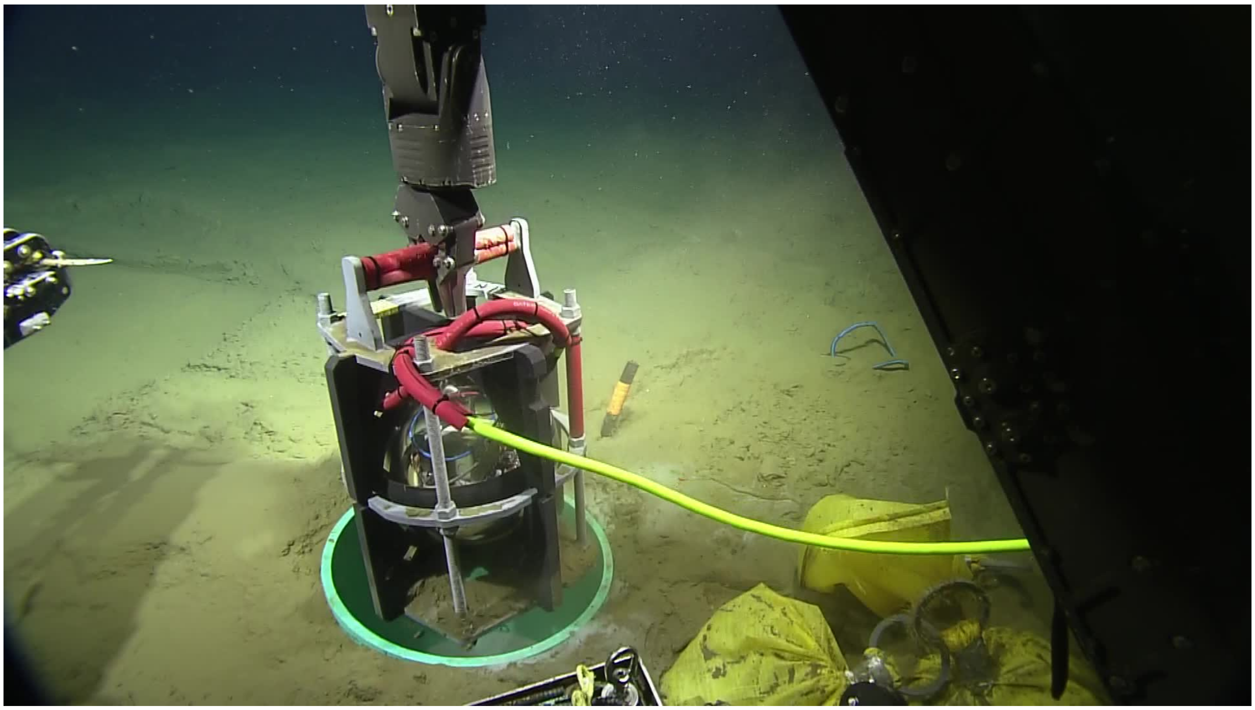


Figure 5: A Nanometrics Titan EA accelerometer is installed in a caisson.

Land-based ONC-owned Instrument Network

Accompanying the ocean-based seismic network, ONC has also installed several land-based stations to augment the terrestrial footprint of the Cascadia EEWS. Project dedicated resources have enabled efficient and expedited installations beyond coordinated efforts with external organizations. The inclusion of these stations has enhanced the EEW network's geographical range, consequently improving overall capability and performance, and adding overall system value. Furthermore, much of this work has supported growing relationships with data partners, end-users, First Nations communities and regional/municipal districts. Details of these installations are discussed in the following sections.

ONC Managed Stations

Several stations are full operational, where others are planned for installation completion before the end of June 2019. Physical installation descriptions of each ONC-owned and operated site are outlined below (and details are listed in Tables 4 through 6). Table 4: The components that may be installed at any EEWS station. vary across sites depending on a number of factors including remoteness, redundancy requirements, power and communication requirements.

Port Alice

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities included at this site included:

- scouting for locations for installation of sensors and infrastructure
- installation of GNSS monument, antenna, receiver and necessary auxiliary equipment;
- installation of seismic vault and strong motion sensor;
- installation of AC charger and batteries;
- installation of electronics enclosure;
- installation of cellular communications modem, antenna and cabling; and
- installation of satellite dish, modem, power supply and cabling.

Strathcona Park

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities included at this site included:

- scouting for locations for installation of sensors and infrastructure
- installation of GNSS monument, antenna, receiver and necessary auxiliary equipment;
- installation of seismic vault and strong motion sensor;
- installation of AC charger and batteries;
- installation of electronics enclosure;and
- installation of satellite dish, modem, power supply and cabling.

Victoria Peak

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities included in this site included:

- scouting for locations for installation of sensors and infrastructure
- installation of GNSS monument, antenna, receiver and necessary auxiliary equipment;
- installation of seismic vault and strong motion sensor;
- installation of AC charger and batteries;
- installation of electronics enclosure;
- installation of cellular communications modem, antenna and cabling; and
- installation of solar power system including batteries, solar panels, circuit protection and charge controller.

Vancouver (ProTrans Facility)

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities included in this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of seismic vault and strong motion sensor; and
- installation of electronics enclosure.

Zeballos

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities included in this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of seismic vault and strong motion sensor;

- installation of AC charger and batteries; and
- installation of electronics enclosure.

Cumberland, Port Hardy, Secret Beach, Taylor River

Due to a delay with the land-use agreements, these stations have not yet been completed. Information has been collected during scouting trips that has been applied to the installation plan for seismic and GNSS instrumentation and infrastructure.

Kwois Creek

Due to environmental constraints this station has not yet been completed. Information has been gathered during a reconnaissance mission that will be considered while mapping out the installation plan for seismic and GNSS instrumentation and infrastructure.

Table 4. Components installed at EEWS station, which vary from station to station.

Component	Make/Model	Description	Number installed
Server	Compulab, Fitlet-H PC	A small, low power, rugged and fanless computer acting as a local server at each EEW site. They are x86-compatible, multicore, rated for high temperature, have 2 network ports, have a 5-year warranty and guaranteed supported for 10 years	4
Cell modem	Redlion, SN-6921-AM	A low power industrial cell modem and router. Provides a second wireless antenna for redundancy and to increase signal quality.	2
Router	Redlion, RAM-6021	A low power industrial wired router, capable of network security and filtering.	2
Power Manager	Ethertek, RMS-300	A low power control board for power monitoring and relay switching. Relays are latching models designed for solar installations.	4
Seismic Sensor	Nanometrics, TitanSMA	A low power 3-axis seismometer with very high sensitivity.	5
GNSS Sensor	Septentrio, PolaRx5 GNSS Receiver	A low power receiver capable of tracking all GNSS satellites.	3
Small Battery	Stark, 125 AGM	Lead acid AGM battery in a similar size as car batteries. 12 V, 125 Ah.	10
Large Battery	Exide GNB, Absolyte 690G-09	Lead acid AGM battery made of stackable 'strings', each 12 V, 480 Ah.	4
AC Charger	Xantrex, TrueCharge2	AGM battery charger with a 3-stage cycle, temperature compensation, and capable of using variable-quality AC power source	3
Solar Charger	Midnite Solar, Classic 150	A controller to charge AGM batteries and provide maximum power point tracking (MPPT) of solar panels. Rated for 96 Amps output at 12 V.	1
Solar Panels	Sunmodule, SW 290	PV solar panel, high efficiency monocrystalline, rated for hail, wind, snow, and salt. 25 year warranty.	3

Table 5. Integrated power sources and communication systems at ONC-owned sites.

Site	Power Source	Primary Comms	Secondary Comms
Cumberland	Solar	Cell	-
Kwois Creek	Solar	Satellite	-
Port Alice	AC	Cell	Satellite
Pt. Hardy	Solar	Cell	-
Secret Beach	Solar	Satellite	-
Strathcona Park	AC	Wireless to private ISP	Satellite
Taylor River	AC	Satellite	-
Victoria Peak	Solar	Cell	-
Vancouver (Protrans)	AC	Private ISP	-
Zeballos	AC	School District Internet	-

Table 6. Station instrument information

Location (IRIS Station Code)	Instrument Model and Serial Number
Cumberland (CMBR)	Nanometrics Titan SMA (S/N 000636) Septentrio PolaRx5 UNAVCO GNSS Receiver SSID 3018552 Septentrio Antenna Chokering B3/E6 SN 5158
Port Alice (PALI)	Nanometrics Titan SMA (S/N 00353) Septentrio PolaRx5 UNAVCO GNSS Receiver SSID 3018383 Septentrio Antenna Chokering B3/E6 SN 5155
Port Hardy (PHRD)	Nanometrics Titan SMA (S/N 000617) Septentrio PolaRx5 UNAVCO GNSS Receiver SSID 3018538 Septentrio Antenna Chokering B3/E6 SN 5177
Strathcona Park (STRA)	Nanometrics Titan SMA (S/N 000840) Septentrio PolaRx5 UNAVCO GNSS Receiver SSID 3018555 Septentrio Antenna Chokering B3/E6 SN 5159
Victoria Peak (VICP)	Nanometrics Titan SMA (S/N 000839) Septentrio PolaRx5 UNAVCO GNSS Receiver SSID 3018534 Septentrio Antenna Chokering B3/E6 SN 5156
Vancouver - ProTrans (ERMD)	Nanometrics Titan SMA (S/N 000834)
Zeballos (ZEBA)	Nanometrics Titan SMA (S/N 000843)
Cumberland (CMBR)	Nanometrics Titan SMA (S/N 000636) Septentrio PolaRx5 UNAVCO GNSS Receiver SSID 3018552 Septentrio Antenna Chokering B3/E6 SN 5158

Integration of ONC-owned Instrument Data into Oceans 2.0

Each ONC station has a similar set-up with a Nanometrics Titan SMA accelerometer, and a Septentrio GNSS Receiver/Antenna pair. Locally at each station, there is a Compulab fitlet which is deployed with the data acquisition code and configured with site particular information. The fitlet is represented as the EEW System

Aggregator (Figure 6), as it collects data from the downstream instruments, derives the EEW parameters for the Titan and uses data from the Titan and GNSS to execute Precise Point Positioning (Precise Point Positioning) algorithms. These algorithms were provided by Canadian Geodetic Survey of Natural Resources Canada with three solutions (Float, Integer and Orbits). To store the computed values, there are three corresponding virtual Precise Point Positioning devices that are represented as aggregator sub-components. For cases in which there are no GNSS devices at a site (e.g., Zeballos), no Precise Point Positioning devices are included.The fitlet or 'EEW System Aggregator' sends derived data (Titan SMA EEW system parameters, and Precise Point Positioning values) to the central ONC archive.

The data acquisition for the derived EEW parameters for the Titan SMAs differs from the Titan EAs as there is

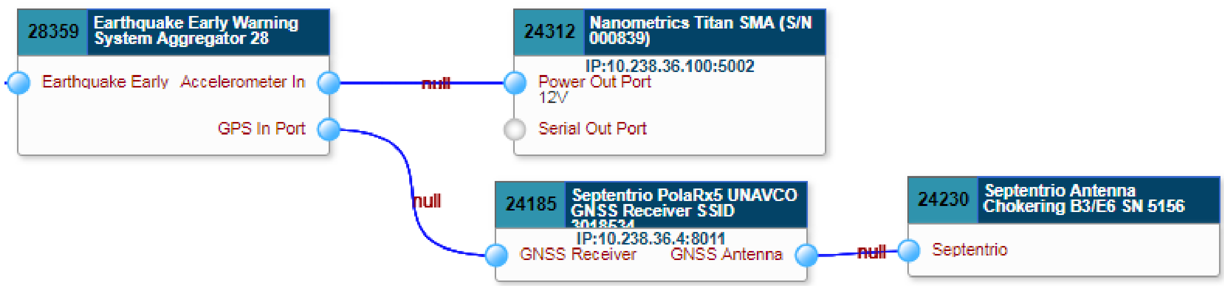


Figure 6. Typical topology of an EEW land station site.

no intervening military machine. Thus, the ONC driver can communicate directly with the instrument, computing the parameters within Oceans 2.0. As such, there is also a more straightforward ability to modify and tweak the various configuration parameters for the algorithm. The raw data is currently not retained, although there is a locally stored buffer which can be manually downloaded in case of an event. A more systematic approach to obtaining and storing raw data segments is anticipated in the commissioning phase.

A typical Precise Point Positioning device reports the following computed values at 1Hz:

- Number of Satellites Tracked
- Number of Satellites Fixed
- North/East Displacement
- Vertical Displacement
- Peak Displacement (Pd)
- Peak Displacement (Pd) Error
- Peak Ground Displacement (Pgd)
- Peak Ground Displacement (Pgd) Error
- North/East/Vertical Offset
- North/East/Vertical Offset Standard Deviation.

Pre-Deployment testing framework for ONC-owned instrumentation

Similar to the subsea accelerometers, the land based accelerometer are first setup in the Pacific Geoscience Centres seismic vault for noise floor and spectral analysis testing. These data are also recorded over a period of one week and compared to the reference instrument co-located in the seismic vault and owned by Natural Resources Canada/Canadian Hazard Information System. The instrument is then transferred to the Marine Technology Centre for Data Acquisition Framework testing procedures.

Data validation of the "Integrated EEW system" that comprises the accelerometer, the GNSS receiver and antenna, and the EEW aggregator with the three Precise Point Positioning solutions is done in two steps.

Additionally, to the seismic data verification steps mentioned above, the GNSS raw binary data is briefly checked for data quality and accuracy by comparing the tested antenna/receiver pair with a reference antenna/receiver pair if available. Otherwise the data from the tested instruments is compared with already archived data in Oceans 2.0 that was recorded at the same geographical location. The second step in the data validation approach confirms the output from Precise Point Position software for the GNSS data and their corrections. However, the current process is still under development and no formal procedures have been developed at this point.

Earthquake Early Warning System Software

In 2015, Ocean Networks Canada was awarded a research software grant to build the Web-enabled Awareness Research Network (WARN). The project focused on providing tsunami and earthquake detection and alerting capability in a proof-of-concept form. Consequently, this project produced the distributed architecture and developed the code base that was subsequently used in support of the current EEWS. The enhancements and sophisticated evolution are discussed here in more detail. The architecture initially developed under the WARN project (Figure 7) follows a distributed processing approach..

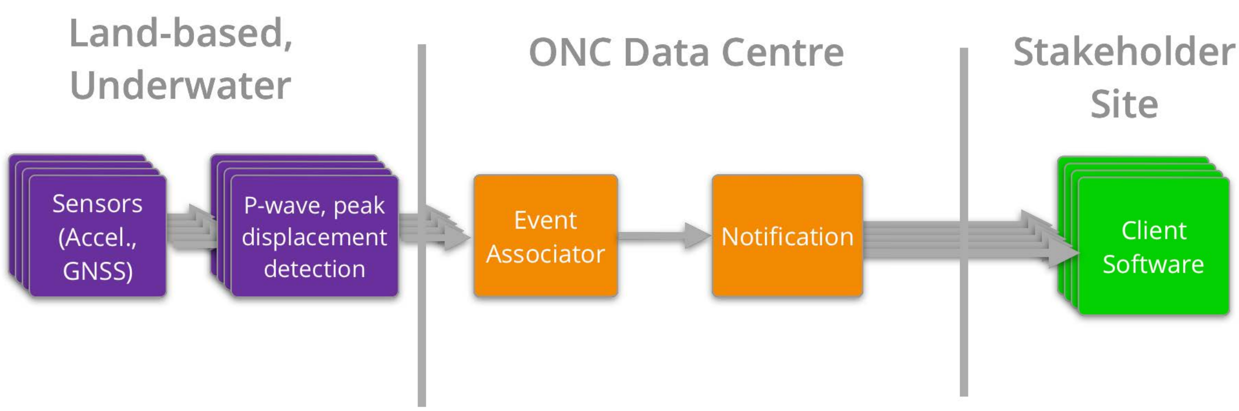


Figure 7.Schematic depiction of the EEW system architecture that shows its distributed nature with processing happening in different locations: sites where sensors are located, data centre and user sites.

The EEWS Software Suite

Graduating from the initial WARN proof-of-concept, ONC has added significant enhancements to the software by upgrading or adding components such as sophisticated event detection algorithms, notification capabilities and decision-making modules. The details of these improvements are summarized in relevant sections below, respectively.

Understanding Event Detection

The problem setting for the EEWS differs from traditional seismology because the time needed to observe and analyze the full wave-form over the total duration of an earthquake cannot be afforded. Algorithms that determine the location of a source, the earthquake epicenter, from just the first arrival times of a wave (in the case of earthquakes, the P-wave) have initially been developed in acoustical engineering (Friedlander, 1987; Schau and Robinson, 1987; Huang and Benesty, 2000; Pirinen, Pertil Visa, 2003; Pirinen, 2006; Gillette and Silverman, 2008) rather than in seismology. Complete seismograms provide a lot more information than just first arrival times of a single phase.

A similar remark applies to algorithms proposed for estimating the final magnitude of an earthquake from just a few seconds of P-wave recordings. More recent research shows that incorporating real-time displacement data from GNSS will provide more robust estimates and updates while a large earthquake unfolds. The algorithms originally developed in the WARN project have thus been extended to process GNSS data and the data from a collocated seismometer into an unbiased displacement time series (Bock et al. 2011, Melgar et al. 2013, Li, 2015, Niu and Xu, 2014). In large earthquakes with magnitudes greater than M5 these data will provide more reliable magnitude estimates also in the early stages of a developing earthquake.

The project has thus implemented two independent algorithms to estimate the earthquake epicenter form at least four detections at different stations in the network. For earthquakes with smaller magnitudes two independent algorithms, one based on the frequency content of the early seismic signal (Wurman, Allen, and Lombard, 2007; Lockman and Allen, 2007), the other based on initial displacement amplitudes (Kuyuk and Allen, 2013) are used to estimate magnitude. For larger earthquakes the magnitude estimates will be continuously updated using data from the unbiased displacements over the total duration of the earthquake (Crowell et al., 2013) .

The technique to collocate a strong motion seismometer and a GNSS instrument is relatively new and only a few sites with collocated instruments exist world wide. The algorithms for the joint processing of seismic and GNSS data so far have been verified with recorded data in offline experiments. ONC in cooperation with the Canadian Geodetic Survey has developed a mechanical platform which allows controlled movements of GNSS antenna and seismometer.

Both instruments are rotated in a circle with a varying turn rate while the accelerometer maintains its orientation in space. The real-time double integration of acceleration under control of a Kalman filter algorithm (Bock et al. 2011, Bar-Shalom, 2001) driven by the GNSS precise point positioning (Precise Point Positioning) must then reproduce the circle with the correct radius. Several experiments have been carried out in this way to verify that the calculations required to generate the Precise Point Positioning data series and the two integration steps work correctly.

The Event Detection Algorithm

The incorporation of geodetic (GNSS) data substantiated the largest change to the initial event detection algorithm. This enhancement directly corresponds to a significantly increased level of accuracy when estimating large magnitude earthquake events. Specifically, inclusion of these data provides the system with two additional magnitude parameters - peak displacement and peak ground displacement - ultimately adding another layer of computational sophistication. These parameters are derived from GNSS raw output data that is then processed using three separate instances of Natural Resources Canada's Precise Point Positioning software (discussed in the previous section). The three instances produce three independent data streams we refer to as the Integer, Float, and Orbit. The varying degrees of accuracy between these streams adds benefits but also complexity. Firstly, no additional corrections to the Orbit stream are applied, thereby rendering it both the most reliable but making it the least accurate solution. Conversely, the Integer and Float streams do receive corrections; however, with the caveat that in the event the data connection is broken and the site is unable to receive corrected data, neither solution will report data at all. Assuming a reliable data connection, unbiased displacement values are computed by combining the individual displacement values retrieved from each separate stream with the incoming acceleration values, using an algorithm named the Kalman Filter (discussed in previous section). More specifically, the x and y displacement values are used to calculate the peak displacement, whereas the x, y and z displacement values provide the peak ground displacement value. Furthermore, the unbiased displacement output obtained from the Kalman Filter is then used to calculate the standard detection over the previous 600 seconds of displacement data, offering an indication of false peak and peak ground displacement triggers caused by noise or other erroneous factors. Instead, for a peak displacement or peak ground displacement value to be considered valid, it is required to be greater than three times the standard deviation. As this may not always be true, we have implemented a standard deviation floor that can be defined on a site-by-site basis in order to account for sections of time that have an unusually small standard deviation. Although the incorporation of GNSS data presents challenges, the solution renders accurate results proving reliable with added redundancy measures. Though important, these geodetic changes constitute only a portion of the enhancements applied to the event detection algorithm.

The two epicentre algorithms, Linearized Least Squares (the method for solving a system of linear equations by minimizing the sum of the squares of the residuals) and Direct Grid Search (DGS), have undergone substantial improvements as well. Previously, when calculating an epicentre, P-wave velocity was assumed to be 6200 m/s. New computational changes include the initial Direct Grid Search and Linearized Least Squares epicentre velocity to be 7000 m/s, where a check has been implemented to gauge if using a smaller or larger velocity might produce a more accurate epicentre, gained via assessment of the quality indicators in these two algorithms; the most likely P-wave velocity between 6000 m/s and 8000 m/s in increments of 500 m/s is determined. Now, only an Linearized Least Squares epicenter is considered accurate if it has a condition number smaller than 30, where previously epicentres with a condition number smaller than 50 were accepted. Furthermore, both algorithms are now required for accurate epicentre determination, where both of the epicentres must be within 80 km of each other. The quality indicators are verified on both epicentres and the one with best quality indicator is accepted and reported.

Additionally, two new magnitude algorithms were added to calculate the peak and peak ground displacement values from the GNSS data obtained. Assuming the magnitude can be determined from the GNSS data, it will be selected as the estimated event magnitude value. If the magnitude cannot be computed from GNSS input, the maximum value determined between the two seismic magnitude parameters (τP, seismic peak displacement) will instead be used to report the estimated event magnitude.

The inclusion of geodetic data has doubled the input volume into the EEWS detection algorithm, consequently increasing the duration of time required for overall processing and reporting. To reduce processing time and optimize software computational performance speeds, all P-wave arrival times are immediately associated within the system, as opposed to waiting 5 seconds for the magnitude parameters to arrive as was previously done.

Finally, several quality checks have been implemented to avoid detection of teleseismic earthquakes. These include verification of the seismic τP and peak displacement values and comparison of the P-wave arrival times across different system sites.

Event Notification Improvements

A substantially upgraded feature to the EEWS software suite is its enhanced ability to provide notifications of approaching seismic events- this notification message is using the Common Alerting Protocol message standard and format. Several new fields have been added to the structured message, specifically a `CApplication Programming InterfaceD` field and `ReferenceIDs` field that allow real-time notification updates. Should an adjustment be required to a previously deployed notification, it will contain the previous message's `CApplication Programming InterfaceD` in it `ReferenceIDs` field. Additionally, the Common Alerting Protocol notification now contains a geocode field describing the estimated earthquake epicentre location. Several pre-existing fields required slight changes to values in order to match the Common Alerting Protocol standard as defined by Public Safety Canada (https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/mrgnc-prprdnss/capcp/index-en.aspx). New fields were also added to include the number of sensors contributing to the epicentre and magnitude estimates as a means to indicate and measure notification accuracy.

Additionally, the notification software now supports the generation of test notifications. Any end-user can easily query a web service to generate a test notification that will be relayed back to them. The web service allows the user to specify the magnitude and epicentre of the earthquake. The purpose of introducing end-user notification testing capability is to support verification and troubleshooting by users for indication of network stability and successful notification delivery and receipt.

The Integration Of Multiple Sources Of Data

The EEW system has been designed to include a small computer that is co-located with the instruments at each land-based site. Alternatively, the subsea instruments are collectively processed by a single central computer operating at a land-based shore station. By adding two new servers capable of individually running the event detection code, the data collected from both land-based and subsea instruments can be combined for optimal detection. Data from both of these system components are delivered to the processing facility at the University of Victoria, Victoria and in Kamloops, British Columbia, Canada. These two servers are intentionally located far apart in order to maintain computational capabilities in the event one of the facilities is damaged. Data are sent to the servers through a messaging platform called ActiveMQ in the form of a 'durable topic'. A durable topic means that if any of the station sources lose connection to power and/or communications, the data message will be stored locally and re-sent when a new connection has been established again. This is especially useful if several sites lose their connectivity briefly during migration to secondary backup circuits.

Titan Driver

The driver collects the raw acceleration data from a three-axis, strong motion accelerometer (e.g. a Nanometrics Titan). The driver processes the data and generates several EEW related parameters as well as retransmits the raw acceleration data to the Kalman filter. The EEW related parameters include displacement values for all three axes once per second. Additionally, in the case of an event detection, the P-wave and S-wave arrival times in addition to the τP and peak displacement values, are transmitted.

Testing the Integration of GNSS and Accelerometer Data

The approach to co-locate a strong motion seismometer and a GNSS instrument is relatively new, with only few demonstrations worldwide. The algorithms necessary for cooperative processing of seismic and GNSS data received simultaneously have only been verified using recorded data in offline experiments. ONC, in coordination with the Canadian Geodetic Survey, has developed a mechanical platform that allows controlled movements of a GNSS antenna and seismometer. Together, these instruments are rotated in a spherical orbit using a varying turn rate while the accelerometer maintains its orientation in space. The real-time double integration of acceleration under control of a Kalman filter algorithm (Bock et al. 2011, Bar-Shalom, 2001) driven by the GNSS Precise Point Positioning software must then reproduce the circle with the correct radius. Several experiments have been executed in this manner to successfully verify that the calculations required to generate the Precise Point Positioning data series and the two integrations steps are correct. There are no historical WARN detected earthquakes that can be used in comparison to recent EEWS detections, so instead and more appropriately, the quality of current solutions are tested and compared against real-time earthquake epicenter, magnitude, and origin data determined after an earthquake event reported by other national organizations (e.g. Natural Resources Canada, Pacific Northwest Seismic Network etc.).

The original Titan driver would collect the raw acceleration data for processing, but not save or retransmit the raw acceleration data. Considering the partnership with Canadian Geodetic Survey and inclusion of the Kalman filter algorithm, the Titan driver required an update to retransmit the raw acceleration data, where it previously only processed the JMA parameter output.

Enhancements necessary for Integration

To enable the collaborations with Natural Resources Canada and Pacific Northwest Seismic Network, necessary changes to support integration with these networks have been implemented and are discussed in this section.

WARN Application Programming Interface and Client

A client library (or client) is a set of software code that offers users the ability to interact with an Application Programming Interface. Specifically, in the case of EEWS, two Application Programming Interface calls have been added to the client library to allow stakeholders to access the status of the system and send out test notifications. Both of these Application Programming Interface calls can be run at an interval that is specified by the end-user. The specific Application Programming Interface call that displays the status of the EEW system returns a complete list of all stations, indicating the ones that are connected and disconnected. Additionally, it also returns a field that reveals if the minimal number of sites required to detect an earthquake are connected or not. A second client call is available to request test alerts using an epicentre and magnitude configured by the user. As the client queries for test alerts, it automatically subscribes the client to begin receiving real notifications.

Backend Support Systems

Additional modifications to the existing code were required to support the inclusion of new remote land stations. Currently, the land-based sites do not have a database connection and many of them are constrained by limited bandwidth access. The initial WARN system relied entirely on the assumption of a database connection in order to load the cache of each site upon startup, where the cache contained the metadata for all of the instruments corresponding to the database. Modifications to the cache loading system were necessary to load site-specific caches, especially considering the remote nature of a subset of stations. Now, during startup, instead of receiving a cache directly from the database, the land sites instead request a cache through a messaging system (ActiveMQ) using a virtual machine located at the University of Victoria. Once a cache request has been received, the virtual machine sends the cache information as a message back through ActiveMQ. Furthermore, rather than distributing cache information for all of the instruments in the database, new restrictions confine the content to include only critical site-specific cache information for 1-4 instruments. The result is a quick exchange of information in order to expedite the cache loads while consuming a fragment of the bandwidth as was previously used.

While faster processing speeds over lower data usage rates is important, processing a large volume of concurrent data is challenging. As a means for improving data exchange, a new ActiveMQ messaging topic was added to support immediate data transfer from all of the EEWS stations to the associator virtual machine for instant event detection. This solution enables multiple servers to associate data simultaneously for added redundancy, where all necessary data is sent to individual servers that has previously subscribed to the corresponding topic. Currently, the system utilizes two associator instances located at the University of Victoria and in Kamloops, British Columbia. As previously mentioned, this geographical separation is intentional in order to maintain full operational capability even during potential widespread devastation specifically affecting the Victoria location.

Testing and Verification

The current testing framework targets each algorithm with unit tests, and includes both simulated and detected earthquake sets crucial for testing the entire event detection process. Each unit test validates the individual algorithms against a set of expected results, so that if the output of the algorithm should change, this is revealed through a failed test. Similarly, the event detection process is tested in an analogous manner, where expected epicentres, magnitude values, and origin times are pre-determined by a given set of earthquake data and compared against generated EEWS values. This also enables verification of improved accuracy as enhancements are added to the event detection algorithm, validation of added rigidity measures that result in the correct rejection of epicentres generated from teleseismic earthquakes, and assessment of the effectiveness of the individual components and entire notification system. Additionally, ongoing collaboration with beta-testers has resulted in verification of the successful receipt of detection notifications within 1-2 seconds of system dispatch.

Performance tests of the event detection process use simulated earthquake data intended to trigger a P-wave detection at all stations. Initially, the software model required several minutes to process the influx of data simultaneously from all stations. Specific enhancements have reduced the time required for processing to 8-9 seconds at present, and continued assessment may reveal ways to improve this even further. Moreover, to extensively test the integration of multiple sources of data, a quality assurance (QA) network has been designed that imitates a live, operational environment. This QA network is capable of receiving simulated device data and subsequently sending false messages for analysis purposes. Experts simulate operational land-based and subsea instruments to send counterfeit event information to the central servers and evaluate the quality, accuracy, reliability and speed of data processing, event detection and notification messages. Together, this investigative approach identifies the strengths and gaps of the current system and its components. This information is used appropriately to develop and implement enhancements intended to increase performance levels as necessary.

Non-ONC Sensor Integration

Among its various mandates, Natural Resources Canada is to deliver nationwide seismic and geodetic information. More specifically, the Pacific GeoScience Centre, the Canadian Geodetic Survey and the Canadian Hazard Information System are three groups that have contributed actively in the development of the Cascadia EEWS. The contributions from these departments have been multifaceted, including support via software, expertise, administration and installation resources. The Pacific GeoScience Centre has provided advice on earthquake science, systems & administrative support, office space and testing facilities. The Canadian Geodetic Survey has supported understanding, calibration and installation of geodetic instruments (GNSS) together with dedicated software integral to earthquake detection. Canadian Hazard Information System has contributed instrumentation and auxiliary/ancillary equipment, provided data and site access, committed equipment and supplies, and offered various levels of field support. The established relationship and ongoing collaboration with Natural Resources Canada has been a critical success factor credited to the current state of the EEWS. Additionally; however, ONC has successfully established important partnerships that span our Canadian borders.

The Pacific Northwest Seismic Network, based in Seattle, operates a large network of seismic sensors in Washington and Oregon State that are relatively identical those used in BC. This network uses similar methods to the Cascadia EEWS, but utilizes different framework architecture in line with the USGS approach. Subsequently, Pacific Northwest Seismic Network and ONC extract similar parameters from their sensors providing opportunity for the successful integration of EEW networks. Ongoing, coordinated efforts have allowed specific subsets of data to be shared, where several Pacific Northwest Seismic Network sensors are now available to ONC. Similarly, the parameters extracted from BC's sensors are made available to Pacific Northwest Seismic Network for inclusion in their own USGS-based earthquake early warning system.

Land-based integration with Natural Resources Canada

Throughout the duration of this 3-year project, Natural Resources Canada was actively involved with the upgrade and amalgamation of their geodetic reference and seismic stations. In a collective effort to promote system integration, pool resources, reduce redundant efforts, utilize current infrastructure, decrease administration, curtail capital costs and expedite timelines, ONC and Natural Resources Canada developed an approach that relied on collaborative efforts. There were 20 Natural Resources Canada stations with existing geodetic instrumentation, where 10 also included seismic equipment. ONC participated and assisted with a variety of office and field activities to upgrade the infrastructure and add seismic instrumentation to these geodetic-only sites. Additional network equipment, power systems, secondary communication channels, ancillary equipment and battery backups were also added to compensate for the additional load in a variety of combinations at each of these 20 sites.

A typical Natural Resources Canada-owned site houses a power source, battery backup, and an internet connection to send raw data directly to a data centre in Ottawa. The EEW system architecture requires a small local server at each site to calculate seismic parameters and send the low-bandwidth data to ONC data centres. Consequently, each site is equipped with one of these computers (fitlet) to enable site-specific on-demand processing that contributes to the overall EEWS.

To integrate the existing Natural Resources Canada stations with ONC requirements, a second router/firewall has been added to each station. This provides an additional secure network intended to isolate Natural Resources Canada network devices from ONC devices, while providing filtering to the internet connection.

Roughly half of the stations are located in weather-dependent locations such as remote mountain tops, limiting possible field work times to the June-October timeframe, except during wildfires. Collaborative efforts between ONC and Natural Resources Canada on these shared sites within the constraints of competing priorities, shared field schedules, required systems support staff and remote site logistics proved to be the most challenging aspect of the physical integration of sensors. The following section details installation efforts by ONC to support these shared sites.

ONC-Natural Resources Canada Managed Stations

Albert Head, Bamfield, Beaver Cove, Chemainus, Quadra Island, Ucluelet (location map in Figure 2)

These stations are completed, commissioned and currently integrated into the EEWS for testing. Important activities at these sites included:

- scouting for locations for installation of sensors and infrastructure;
- installation of seismic vault and strong motion sensor;
- installation of AC charger and batteries; and
- installation of electronics enclosure.

Brooks Peninsula

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of GNSS monument, antenna, receiver and necessary auxiliary equipment;
- installation of seismic vault and strong motion sensor;
- installation of radio communications equipment;
- installation of solar power system including batteries, solar panels, circuit protection and charge controller;
- installation of electronics enclosure; and
- installation of cellular communications modem, antenna and cabling.

Eliza Dome

This station is completed, commissioned and currently integrated into the EEWS for testing.Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of seismic vault and strong motion sensor;
- installation of solar power system including batteries, solar panels, circuit protection and charge controller;
- installation of electronics enclosure; and

- installation of satellite dish, modem, power supply and cabling.

Gold River

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of seismic vault and strong motion sensor;
- installation of radio communications equipment;
- installation of AC charger and batteries;
- installation of electronics enclosure; and
- installation of satellite back-up communications.

Holberg

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- iinstallation of electronics enclosure; and
- installation of cellular communications modem, antenna and cabling.

Jordan River

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of seismic vault and strong motion sensor;
- installation of solar power system including batteries, solar panels, circuit protection and charge controller;
- installation of electronics enclosure; and
- installation of cellular communications modem, antenna and cabling; and
- planning for the installation of satellite dish, power supply and cabling.

Lake Cowichan, Survey Mountain

These stations are completed, commissioned and currently integrated into the EEWS for testing. The activity at these sites only included the installation of Fitlet and power wiring.

Mount Grey

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of GNSS monument, antenna, receiver and necessary auxiliary equipment;
- installation of seismic vault and strong motion sensor;
- installation of AC charger and batteries;
- installation of solar power system including batteries, solar panels, circuit protection and charge controller;
- installation of electronics enclosure; and
- installation of cellular communications modem, antenna and cabling.

Myra Falls

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of seismic vault and strong motion sensor;
- installation of solar power system including batteries, solar panels, circuit protection and charge controller;
- installation of electronics enclosure; and
- installation of satellite dish, modem, power supply and cabling.

Newcastle Ridge

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of GNSS monument, antenna, receiver and necessary auxiliary equipment;
- installation of seismic vault and strong motion sensor;
- installation of AC charger and batteries;
- installation of electronics enclosure; and
- installation of satellite dish, modem, power supply and cabling.

Nootka Lighthouse

This station is completed, commissioned and currently integrated into the EEWS for testing.Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of AC charger and batteries;
- installation of electronics enclosure; and
- installation of satellite dish, modem, power supply and cabling.

Port Renfrew

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of AC charger and batteries; and
- installation of electronics enclosure.

Port Alberni

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of seismic vault and strong motion sensor;
- installation of AC charger and batteries;
- installation of electronics enclosure; and
- installation of satellite dish, modem, power supply and cabling.

Sidney (Pacific Geoscience Centre)

This station is completed, commissioned and currently integrated into the EEWS for testing.Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of seismic vault and strong motion sensor;
- installation of AC charger and batteries;
- installation of electronics enclosure; and
- installation of cellular communications modem, antenna and cabling.

Tofino

This station is completed, commissioned and currently integrated into the EEWS for testing. Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure; and
- installation of seismic vault and strong motion sensor.

Woss

This station is completed, commissioned and currently integrated into the EEWS for testing.Important activities at this site included:

- scouting for locations for installation of sensors and infrastructure;
- installation of AC charger and batteries; and
- installation of electronics enclosure.

Fair Harbour, Sharp Point, Tahsis

Due to weather constraints this station has not yet been completed. Information has been gathered during a reconnaissance mission that has been considered and applied to the current installation plan for seismic instrumentation and infrastructure.

Mount Maynard

Due to conflicting priorities this station has not yet been completed. Information has been gathered during a reconnaissance mission that has been considered and applied to the current installation plan for seismic instrumentation and infrastructure.

Nanoose

Due to delays with the land-use agreement this station has not yet been completed. Information has been gathered during a reconnaissance mission that has been considered and applied to the current installation plan for seismic instrumentation and infrastructure. Additionally, an electronics enclosure has already been installed.

There are a range of physical components that make up an installed EEWS station (Tables 7 through 9). Station architecture varies over most sites, and is also dependent on a number of factors like remoteness, redundancy requirements, ONC versus ONC-Natural Resources Canada managed equipment, power and communication requirements, etc.

Table 7. List of physical components that are selected to complete an EEWS station.

Component	Make /Model	Description	Number installed
Server	Compulab, Fitlet-H PC	A small, low power, rugged and fanless computer acting as a local server at each EEW site. They are x86-compatible, multicore, rated for high temperature, have 2 network ports, have a 5-year warranty and guaranteed supported for 10 years	22
Cell modem	Redlion, SN-6921-AM	A low power industrial cell modem and router. Provides a second wireless antenna for redundancy and to increase signal quality.	2
Router	Redlion, RAM-6021	A low power industrial wired router, capable of network security and filtering.	18
Power Manager	Ethertek, RMS-300	A low power control board for power monitoring and relay switching. Relays are latching models designed for solar installations.	14
Seismic Sensor	Nanometrics, TitanSMA	A low power 3-axis seismometer with very high sensitivity.	12
Small Battery	Stark, 125 AGM	Lead acid AGM battery in a similar size as car batteries. 12 V, 125 Ah.	12
Large Battery	Exide GNB, Absolyte 690G-09	Lead acid AGM battery made of stackable 'strings', each 12 V, 480 Ah.	12
AC Charger	Xantrex, TrueCharge2	AGM battery charger with a 3-stage cycle, temperature compensation, and capable of using variable-quality AC power source	2
Solar Charger	Midnite Solar, Classic 150	A controller to charge AGM batteries and provide maximum power point tracking (MPPT) of solar panels. Rated for 96 Amps output at 12 V.	2
Solar Panels	Sunmodule, SW 290	PV solar panel, high efficiency monocrystalline, rated for hail, wind, snow, and salt. 25 year warranty.	10
Wireless Radio	Freewave, FGR2-PE	A low power, rugged, industrial-grade point-to-point radio using spread-spectrum on the 900 MHz ISM band.	1

Table 8. Power and communication specifics for each land-based site.

Site	Power Source	Primary Comms	Secondary Comms
Albert Head	AC	Telus ADSL (NRCan)	-
Bamfield	AC	Telus ADSL (Bamfield Science Centre)	-
Beaver Cove	AC	Cell (NRCan)	-
Brooks Peninsula	Solar	Wireless link to cellular (ONC)	Plan for satellite
Chemainus	AC	ADSL (NRCan)	-
Eliza Dome	Solar	Satellite (ONC)	-
Fair Harbour	AC	Satellite (ONC)	-

Site	Power Source	Primary Comms	Secondary Comms
Gold River	AC	Wireless link to private ISP	ISP provides satellite backup
Holberg	Solar	Wireless link to cellular (ONC)	Plan for satellite
Jordan River	Solar	Cell (NRCan)	Plan for satellite
Lake Cowichan	AC	Cellular (NRCan)	-
Maynard	Solar	Wireless link to cellular (ONC)	Plan for satellite
Mt. Grey	Solar	Cellular (NRCan)	-
Myra Falls	Solar	Wireless to private ISP (NRCan)	Satellite (ONC)
Nanoose	AC	Cell (ONC)	-
Newcastle Ridge	AC	Cellular (NRCan)	-
Nootka Lightstation	AC	Satellite (ONC), iDirect	-
Pacific Geoscience Centre	AC	Cell ONC	-
Port Renfrew	AC	Cable (NRCan)	-
Pt. Alberni	AC	Cell (NRCan)	Satellite (ONC)
Quadra Isl.	AC	Wireless link to private ISP	-
Sharp Point	Solar	Cell (NRCan)	-
Survey Mt.	Solar	Cellular (NRCan)	-
Tahsis	AC	Wireless to private ISP	-
Tofino	AC	ADSL (NRCan)	-
Ucluelet	AC	ADSL (NRCan)	ONC Satellite
Woss	Solar	Cellular (NRCan)	-

Table 9. A summary of the instrument model and serial numbers deployed at each EEW land station.

Location (IRIS Station Code)	Instrument Model and Serial Number
Albert Head (AL2H)	Nanometrics Titan SMA (S/N 000619) Septentrio PolaRx5 GNSS Receiver SSID 3016127 Trimble Antenna Chokering TRM59800 SN 5112354071
Bamfield (BAMF)	Nanometrics Titan SMA (S/N 000637) Septentrio PolaRx5 GNSS Receiver SSID 3015944 Septentrio Antenna Chokering B3/E6 SN 5120
Beaver Cove (BCOV)	Nanometrics Titan SMA S/N 000349) Septentrio PolaRx5 UNAVCO GNSS Receiver SSID 3016104 Septentrio Antenna Chokering B3/E6 SN 5122

Location (IRIS Station Code)	Instrument Model and Serial Number
Brooks Peninsula (BPEB)	Nanometrics Titan (S/N 002582) Nanometrics Centaur (S/N 1036) Septentrio PolaRx5 GNSS Receiver SSID 3016170 Septentrio Antenna Chokering B3/E6 SN 5117
Chemainus (SC04)	Nanometrics Titan SMA (S/N 000635) Septentrio PolaRx5 GNSS Receiver SSID 3016004 Septentrio Antenna Chokering B3/E6 SN 5148
Eliza Dome (ELIZ)	Nanometrics Titan (S/N 1109) Septentrio PolaRx5 GNSS Receiver SSID 3016090 Septentrio Antenna Chokering B3/E6 SN 5133 Nanometrics Centaur (S/N 2598)
Gold River (GLDR)	Nanometrics Titan SMA (S/N 000844) Septentrio PolaRx5 GNSS Receiver SSID 3016119 Septentrio Antenna Chokering B3/E6 SN 5141
Hoberg (HOLB)	Nanometrics Titan (S/N 000945) Nanometrics Centaur (S/N 1873) Septentrio PolaRx5 GNSS Receiver SSID 3016155 Septentrio Antenna Chokering B3/E6 SN 5130
Jordan River (JORD)	Nanometrics Titan SMA (S/N 000618) Septentrio PolaRx5 GNSS Receiver SSID 3015949 Septentrio Antenna Chokering B3/E6 SN 5144
Lake Cowichan (CLRS)	Nanometrics Titan (S/N 000943) Nanometrics Centaur (S/N 1867) Septentrio PolaRx5 GNSS Receiver SSID 3016152 Septentrio Antenna Chokering B3/E6 SN 5134
Mount Grey (MGRB)	Nanometrics Titan (S/N 001110) Nanometrics Centaur (S/N 2082) Septentrio PolaRx5 GNSS Receiver SSID 3015935 Septentrio Antenna Chokering B3/E6 SN 5121
Myra Falls (MYRA)	Nanometrics Titan SMA (S/N 000357) Septentrio PolaRx5 GNSS Receiver SSID 3016053 Septentrio Antenna Chokering B3/E6 SN 5145
Newcastle Ridge (NCSB)	Nanometrics Titan (S/N 1113) Nanometrics Centaur (S/N 2506) Septentrio PolaRx5 GNSS Receiver SSID 3016122 Septentrio Antenna Chokering B3/E6 SN 5127
Nootka Lighthouse (NTKA)	Nanometrics Titan (S/N 001121) Nanometrics Centaur (S/N 2600) Septentrio PolaRx5 GNSS Receiver SSID 3016059 Septentrio Antenna Chokering B3/E6 SN 5140
Port Alberni (PTAL)	Nanometrics Titan SMA (S/N 000845) Septentrio PolaRx5 GNSS Receiver SSID 3016071 Septentrio Antenna Chokering B3/E6 SN 5147

Location (IRIS Station Code)	Instrument Model and Serial Number
Port Renfrew (PTRF)	Nanometrics Titan (S/N 000969) Nanometrics Centaur (S/N 2100) Septentrio PolaRx5 GNSS Receiver SSID 3016110 Septentrio Antenna Chokering B3/E6 SN 5123
Quadra Island (QUAD)	Nanometrics Titan SMA (S/N 000836) Septentrio PolaRx5 GNSS Receiver SSID 3016107 Septentrio Antenna Chokering B3/E6 SN 5126
Sidney - PGC (PGC5)	Nanometrics Titan SMA (S/N 000640) Septentrio PolaRx5 GNSS Receiver SSID 3016100 Septentrio Antenna Chokering B3/E6 SN 5118
Survey Mountain (SYMB)	Nanometrics Titan (S/N 000895) Nanometrics Centaur (S/N 1801)
Tofino (TFNO)	Nanometrics Titan SMA (S/N 000642) Septentrio PolaRx5 GNSS Receiver SSID 3016109 Septentrio Antenna Chokering B3/E6 SN 5125
Ucluelet (UCLU)	Nanometrics Titan SMA (S/N 000643) Septentrio PolaRx5 GNSS Receiver SSID 3016064 Septentrio Antenna Chokering B3/E6 SN 5132
Woss (WOSB)	Nanometrics Titan (S/N 000904) Nanometrics Centaur (S/N 1896) Septentrio PolaRx5 GNSS Receiver SSID 3016069 Septentrio Antenna Chokering B3/E6 SN 5128

Pre-Deployment testing framework for ONC-Natural Resources Canada managed stations

ONC personnel do not have access to Natural Resources Canada owned instruments prior to deployment into the field. Consequently, pre-deployment raw data cannot be validated, documented or verified. Similarly, data validation of the "integrated EEW system" for these instruments was also not possible for this reason.

Integration of Natural Resources Canada-owned Instrument Data into Oceans 2.0

Data integration for Natural Resources Canada-owned instruments is identical to the process used for ONC-owned instruments. The metadata integration, however, follows a different process since the instruments are typically not received, tested and processed at ONC prior to installation. Natural Resources Canada maintains their own metadata files for their instrumentation, which is not all publicly available. Most Natural Resources Canada geodetic stations are part of the International GNSS Service and, therefore, GNSS antenna monument metadata are available in .log files on an ftp site for those sites only (up to a few months after a new deployment). Some metadata pertaining seismic instruments is partially available in the Canadian National Seismograph Network website, but only station codes, coordinates and deployment dates can be somewhat inferred from this information. As ONC relies on knowledge of serial numbers to create new device entries in Oceans 2.0, the Data Stewardship team maintains frequent communication with Natural Resources Canada to find out serial numbers, instrument model, deployment dates and coordinates, when this information is not openly available. Efforts have also been made to define a strategy for station codes that can be as consistent as possible across ONC, Natural Resources Canada and IRIS to maximize interoperability. A more functional service agreement for metadata and information exchange is underway.

Integration with the Pacific Northwest Seismic Network

The data exchange between the Pacific Northwest Seismic Network and ONC is a two-way flow where data from either organization (specifically extracted key parameters from detected events) are flowing to the other party for further processing and integration. The flow is taking place between computers that are interconnected using specific message passing software. The link between the two is over the high-speed research network operated in Canada by CANARIE, guaranteeing the minimum possible latency between the sites in Victoria and Seattle, and Kamloops.

This exchange allows for a dramatically expanded geographical earthquake source coverage for both sides, essentially making the entire subduction zone "visible" to both Canada and the US, with minimal possible latency and therefore maximum warning time in most configurations.

Detailed Components for Successful interoperability

Two new topics were created in the ActiveMQ messaging broker to enable the processing and incorporation of data from Pacific Northwest Seismic Network into the EEWS and to support the delivery of valuable data from the EEWS to Pacific Northwest Seismic Network. New code changes were applied to receive and reformat Pacific Northwest Seismic Network messages so they can be processed by ONC's event detection algorithms. The Pacific Northwest Seismic Network sites have several more p-wave triggers when compared to ONC's EEWS, so implementing additional checks were necessary to filter out false detections from these sites. The data received from Pacific Northwest Seismic Network is archived into Oceans 2.0, requiring additional software changes to support the ingestion of necessary metadata into ONC's database and process incoming data automatically. These archived data (in the form of earthquake detections) are replayed back in an offline environment internally for analysis and the results are used to improve the current algorithms.

The current architecture of the EEWS relies on messages relayed through ActiveMQ as serialized java objects. This added a level of complication for data exchange and integration with Pacific Northwest Seismic Network, as the Pacific Northwest Seismic Network system depended on the need to deserialize the java object into a C++ object. Rather, software improvements were applied to convert the EEWS messages into JSON format prior to dispatch to the Pacific Northwest Seismic Network system. These changes improved data readability, and streamlined data processing as they alleviated the requirement for additional information that is not currently provided with the EEWS messages. For example, the latitude and longitude of each station is archived in the Oceans 2.0 database, though Pacific Northwest Seismic Network also required this information to be packaged with incoming messages. Now, both parties can automatically exchange data without the need for repackaging or accessory details.

End-User Testing

Overview

ONC, with the support and approval of Emergency Management BC, has undertaken a process to engage with EEW End-users from a variety of sectors. These include transportation, health, first responders/local government, utilities, and public alerting. This process mirrors that of the ShakeAlert EEW system under development by the US Geological Survey and State partners in the US.

End-user workshop

On April 19, 2017, ONC conducted a full-day workshop with a broad cross section of potential End-users (Table 10). The plenary group was split into three smaller groups of about 10 people each to discuss three specific topics related to the end-use of EEW. These groups spent about an hour discussing each topic and then rotated to another topic. The plenary group then reconvened to summarize the main discussion points and to talk about next steps.

Table 10. List of participants in the prospective EEW user group workshop held in April 2019.

Title	Organization	Sector
Director	YVR	Industry
Manager, Emergency Programs	City of Burnaby	Local Gov't
Coordinator, Emergency Program	District of Tofino	Local Gov't
Manager of Engineering	District of Tofino	Local Gov’t
Director, HSQE and Technical Services	Protrans	Industry
	Protrans	Industry
Manager of Emergency Services	Powell River	Local Gov't
Senior Integrity Engineer	Fortis	Industry
Disaster Recovery Specialist	Translink	Industry
Senior Manager	BC Housing	Prov Gov't
Regional Program Coordinator	Public Safety Canada	Fed Gov't
Operations Facilities Engineer IT	UBC	University
Deputy Fire Chief	Delta	Local Gov’t
Seismic Specialist	EMBC	Prov Gov’t
Seismic Co-op	EMBC	Prov Gov’t
Professor	SFU	Academia
Capt – mass notification/EQ plan	DND	Fed Gov’t
Manager, Controls	Kinder Morgan	Industry
Supervisor, Control Centre	Kinder Morgan	Industry
Program Manager, Utilities	MetroVan	Local Gov’t
Manager, Initiatives and Performance	Health Emergency Management BC	Prov Gov’t
Founder	Hello Ventures	Industry
Entrepreneur	Go To Safety	Industry
Director of Emergency Management	Translink	Industry
Director of Rail Operations	Translink	Industry
Project Manager Bridges	Translink	Industry
Bridge and Parking Operations	Translink	Industry
Director of Strategy and Business	Softac	Industry
Rapid Alerting Co-op	ONC	Academia
Program Manager	ONC	Academia

Title	Organization	Sector
Project Sponsor	ONC	Academia
Business Analyst	ONC	Academia
Senior Bridge Engineer	MoTI	Prov Gov't
Seismic Health Monitoring	MoTI	Prov Gov't

End-user Pilots

EEW End-user testing took place serial following these steps: (1) technical discussion; (2) software Application Programming Interface integration; (3) initial testing and performance reporting; (4) EEW workshop and training; and (5) full systems test.

Technical discussion

ONC initiated connections with the pilot's technical point of contact, as well as with a technically knowledgeable staff within the organization, and directed them on how to connect and receive the EEW notification. Allowing a computer server to receive an alert was the minimum criteria for testing, however, some End-user explored the integration of test alerts into automated systems (automatic doors, elevators and staff announcements, etc.).

Software Application Programming Interface integration

ONC's Application Programming Interface client code was installed on the selected workstation(s).

Initial testing and performance reporting

Tests of connections were made to ensure that things were working properly.

EEW Workshop/Training

EEW training gave an overview of the technology and how it can be applied to various contexts. This training included Operations staff, safety officers, and appropriate representatives interested in earthquake safety. Background information on the technology and its application in other jurisdictions, along with information on the potential benefits and limitations of the system were presented along with scenario-based table-top exercises to explore the use of EEW within different contexts. Pre- and post-workshop surveys were delivered to allow for feedback and further commentary from participants.

Full systems test

Coinciding with ShakeOut, 2018, a full systems test was carried out at 10:17am on October 18th, giving End-user test participants an opportunity to practice what they might do with 60 seconds early warning before their ShakeOut drill.

Pilot tests were conducted with Protrans (Canada Line), Fortis, Pelmorex, and the District of Oak Bay and are continuing with additional pilot proposals from BC Ferries, Emergency Management BC and Health Emergency Management BC.

First Nations Engagement Planning

ONC's approach to First Nations engagement for this project falls under ONC's Indigenous Community Engagement Plan and Strategic Plan. The approach focuses on building long-term relationships with communities through project-based engagements. As development of the EEW system and integration with neighbouring networks continued to evolve throughout the year, ONC was not in a position to engage in detailed planning with First Nations until the final months of the fiscal year. It is imperative that engagement planning be done collaboratively with First Nations to ensure that the requirements and needs of communities are met. Now that the EEW system is entering the commissioning phase, ONC plans to develop partnerships with communities to evaluate the system's utility for First Nations, which will result in a detailed First Nations Engagement Plan specific to Earthquake Early Warning. This work is planned to continue throughout the next fiscal year.

The following First Nations and Indigenous organizations were engaged in FY18/19 and have expressed interest in participating earthquake and tsunami preparedness related work:

- North Coast Skeena First Nations Stewardship Society
- Nuu-chah-nulth Tribal Council
- Central Coast Indigenous Resource Alliance
- Kitsumkalum First Nation
- Metlakatla First Nation
- Tseshaht First Nation
- Huu-ay-aht First Nation
- Heiltsuk First Nation
- Haisla First Nation
- Tsleil-Waututh First Nation
- Haida Nation
- Gitga'at First Nation.

Explicit commitments for involvement as beta-testers were made by Tseshaht First Nation and Pacheedaht First Nation.

Beta-Testing Approach

For the preliminary stage of beta-testing, two First Nations (Tseshaht First Nation and Pacheedaht First Nation) were selected to participate in the development of scenarios and participate in a beta-test exercise. These nations were selected primarily as they expressed high interest and commitment to the project. A secondary consideration was that they differ significantly in their geographic locations and access to infrastructure. Tseshaht First Nation is located in and around Port Alberni, BC at the end of Alberni Inlet, has a mostly urban population and access to high-speed Internet and cell phone service. Pacheedaht First Nation is located near Port Renfrew, BC, on the west coast of Vancouver Island. As Pacheedaht territory is on the exposed west coast, Pacheedaht First Nation members are at significant risk of earthquake and tsunami damage with little time for warning. The reserve is accessed by two bridges. Port Renfrew does not have cell phone service, and internet service is significantly slower than in urban centres.

In the year timeline of the project, there was insufficient time to design, develop, and implement more than one test scenario. It was decided to proceed with a scenario and pilot workshop with Pacheedaht First Nation. Over the coming year, ONC plans to continue engagement with Tseshaht First Nation and to include other nations in testing if possible as well. It is important for the over all proof of readiness of the system to demonstrate its potential with multiple First Nations as their requirements and locations differ significantly.

First Nations Workshop

EEW End-user training and scenario-based exercise material were developed for a workshop held on March 19th at the Health Centre in the Pacheedaht First Nation near Port Renfrew, BC. Workshop participants were organized by Band Management staff and included a broad cross-section of community members. An agenda was developed and distributed to attendees along with a brochure detailing information related to the workshop.

Workshop material included a two-part survey that was distributed to attendees prior to the commencement of the workshop as well as two exercise scenarios that were presented for workshop discussion purposes. A short presentation on EEWS was delivered as background information, which was followed by the example earthquake scenarios and an open discussion with community members. A summary of the workshop is under development.

Education and Training Material

ONC developed a full educational module to explain the science of earthquakes and tsunamis, earthquake early warning technology, and examine the potential impacts of earthquake events. The module includes interviews with Nuu-chah-nulth knowledge holders who recount the impacts of the 1700 Cascadia subduction zone event and the 1964 Alaskan earthquake on coastal BC First Nations' communities. The training materials in the module are suitable for use with a broad audience including youth and adult students, educators, and the public.

The educational module was piloted in Port Alberni with Indigenous students and educators on September 19-20, 2018 at the Alberni Aquarium and Stewardship Centre. Based on feedback from this event, materials were refined and a second pilot was conducted October 18-21, 2018 at the Canadian Network for Environmental Education and Communication conference. The education and training materials were then shared with Indigenous educators at a booth at the First Nations Education Steering Committee conference in Vancouver from November 22-24, 2018. Collaboration was initiated with Emergency Management BC at this conference in order to coordinate communications and outreach efforts related to earthquake early warning, and this partnership is ongoing.

The materials developed to-date do not address all of the details of the full EEW system, as it was still under development until March 2019. The next step will be to extend the educational module to include a targeted description of the system implementation with specific information for First Nations' use of the system. It was not feasible to produce a dedicated booklet or brochure containing these details by the end of the present project, but ONC plans to continue this work in the next phase should it be desired by the First Nations partners in the project.

Summary of First Nations Engagement

Earthquake early warning is of high interest to all the coastal Indigenous communities contacted during the present project. ONC will continue to engage with the nations that have expressed interest in partnering with and participating in the important phase dedicated to system commissioning during FY19/20.

EEWS Operational Transition: System Commissioning

The Cascadia EEWS is approaching the operational capability to serve a variety of stakeholders in southwestern British Columbia. Before the network can be officially launched publicly, it requires extensive verification and validation for accuracy and reliability. This stage is referred to as system commissioning.

The system commissioning process for the EEWS is critical to ensuring that all system components are properly designed, installed, tested, operational and maintainable. Moreover, the system will be further improved, enhanced and expanded as necessary to optimize its overall reliability and accuracy to detect Cascadia events and provide appropriate notifications.

The activities planned in order to achieve successful commissioning of the EEWS are discussed herein. Together, these activities represent the integrated application of specific techniques and procedures required to check, test and validate each operational component, module, subsystem and of course the system in its entirety. Furthermore, improvements and enhancements will be added as required to achieve the optimum level of operational reliability.

This phase will also provide important information needed to identify realistic maintenance schedules and the costs associated with live operations. Relevant standard operating procedures will be developed and documented with the intent to maximize the longevity of performance and operational functionality. Similarly, geographical and regional contributions of individual stations and system sub-components of the EEWS will be assessed in their ability to contribute to the overall system performance. Furthermore, additional items such as the possibility to add future data partners, end-users and stakeholders will be documented. Relevant training material, system monitoring tools and overall system performance targets and objectives will be both explored and documented and/or developed. Lastly, extensive efforts will be focused on the development of a comprehensive transitioning plan documenting the anticipated shift to live operations.

This important phase will explore and map out essential elements required to launch the system with a high degree of confidence in its reliability, performance and effective management.

Commissioning Plan

This phase will support standard sensor infrastructure-commissioning practices published both internally and externally, and as recommended by international experts. Commissioning will verify the performance and validate the outputs of the overall system through testing from small magnitude earthquake events that frequently occur in this region. Moreover, artificial scenarios for other types of events will also be utilized for system calibration.

Specifically, ONC will support the following key infrastructure-commissioning activities, which are described in more detail in relevant sections:

Validation of the overall system through external peer review; verification of the output quality; overall calibration and fine tuning of the sensors; redundancy improvements for both sensors and central system; testing with real and simulated events as well as with new end-users.

During the commissioning phase, transition support documents will be prepared or frequently updated, and various agreements will be renewed and/or created.

Validation of the Architecture, Concepts, Algorithms and Implementations

ONC will invite an expert review panel to study the Earthquake Early Warning system as designed and implemented and to provide any improvement recommendations to be subsequently implemented. The panel will be composed of international experts and will meet in Victoria for a review intended to take place during the summer of 2019.

Verification of the Science and Data Quality

The accuracy of the data coming from the various sensors at each site and from the central associator will be evaluated and monitored. Throughout the commissioning period, modifications to calibration, trigger thresholds, and software and algorithms will be implemented to improve the quality of the system's output.

Sensor Installations Fine-Tuning

Based on ONC's experience with sensor networks, regular maintenance of both the land based and offshore sensors is necessary for success. Commissioning will include a visit to most sites to improve instrument performance, as well as communication and power systems as required. This work will also establish the annual cost of onshore field servicing.

Redundancy Improvements

System reliability and operational safety lies in redundancy. Including several layers of station, networking and software redundancy will ensure system quality assurance and control are never compromised beyond acceptable levels.

Stations and Sensors

To maximize the uptime of the EEW system, the introduction of redundant instruments and stations will help maintain the minimum number of sensors necessary to contribute to event detection, even following the loss of key sites constrained by lengthy repair times (e.g., inaccessibility during winter). Similarly, introducing more data communication channels at each site will improve the overall uptime, redundancy, and detection capabilities. ONC plans to monitor and evaluate the current system in order to optimize redundancy measures where appropriate. Specifically, this entails:

- New and/or enhanced power and communications systems, both station based and system wide. This will ensure that data flow remains uninterrupted on a system scale.
- Optimization of redundant sophisticated software programs capable of performing automated checks of critical system components.
- System expansion to improve geographical detection accuracy. By increasing the number of stations contributing to the overall system, event detection reliability and accuracy increases, and emergency repair station costs are significantly reduced, maintenance schedules are afforded greater flexibility and system-wide performance is significantly improved leaving an overall diminished risk of system fault or failure. This expansion will be guided by scientific advice.

Central computing facility redundancy improvements

A redundant central computing environment located in Kamloops, BC mitigates the risk of losing the primary system in Victoria. The commissioning phase will entail continued stress tests intended to demonstrate the EEW system's ability to deliver notifications under the most dire circumstances.

System testing with real and simulated data

Based on naturally occurring earthquakes (an average of two per month), commissioning will utilize these data from each real event to re-test the full system following software updates. Moreover, simulated data will reproduce other event types in our region of interest and exercise the overall system.

Enterprise Risk Management

The enterprise risk management framework in place at ONC will track and mitigate strategic and operational risks via a risk register. Specifically, this risk register will identify risk areas, probability of occurrence, expected impact and mitigation measures, and will be assessed quarterly in order to properly manage uncertainties that will be linked to mitigation actions.

End-user Engagement

Commissioning will expand and continue testing with major infrastructure operators, communities, first responders, and First Nations.

Service Level Agreements

Commissioning will evaluate the overall system's performance for the purpose of determining the data needed to establish service level agreements with end users. Agreements will include expected uptime, final earthquake source region coverage, minimum and maximum warning times, as well as maximum probability of false positives and missed detections.

Agreements with partners

Inter-organization data exchange agreements, specifically with Natural Resources Canada and Pacific Northwest Seismic Network will be renewed. In particular, an Natural Resources Canada-ONC site co-management agreement will outline the modalities of site maintenance, troubleshooting, response times to stations outages, information sharing, and cost saving measures.

The Natural Resources Canada-ONC agreement will specifically consider:

- seamless and optimal instrument and station maintenance;
- improved station performance;
- ideal effective and efficient site and system-based troubleshooting;
- substantially reduced maintenance and repair costs;
- significantly decreased response and repair times;
- increased operational value;
- transparent and rich information sharing; and
- lower overall operational system costs.

ONC has developed a very flexible and granular approach for supporting a multitude of use cases with partners. Data agreements with each partner will outline:

- data ownership and role attributions for data products for dataset metadata records and citations;
- data policy details like usage and access restrictions;
- mechanisms and timelines for metadata and data exchange; and
- termination conditions.

Documentation outlining standard operating procedures and best practices

Inspired by best practices in other jurisdictions, and adapted to the circumstances particular to our environment, the documentation will outline the maintenance requirements for the ONC EEW system, including schedules, priorities, and describe a minimum viable system. The documentation will also include training for staff and operators of the system, and will contain items such as suitable maps and drawings, instrument interference patterns, and acceptable station noise levels.

For each instrument type, documentation is underway to currently capture and intends to be enhanced and expanded for the following items:

- Make and model information;
- Networking details – ports, IP addresses, baud rates, time synchronization, cables;
- Data acquisition and control description;
- Hardware details – maximum depth rating, mounting requirements;
- Calibrations – formulas, sheets, in-situ benchmarks;
- Controlled vocabulary mappings;
- Site characterization assessment/needs;
- Orientations – how to define and record;
- Data distribution set up – data products, post-process routines, linked data relationships;
- Attributes – configuration parameters for data acquisition, data products;
- Manufacturer software notes; and
- Other useful resources.

Operational Transition Guideline

The transition to operations document will outline the steps necessary for a successful operation of the infrastructure and system components, including a description of all required operation support staff roles and responsibilities.

Acquisition of a Station Component Replacement Inventory

Commissioning will include purchasing spare sensors so that ongoing maintenance is robust.

Development of Acceptance Criteria

The acceptance criteria will be determined through consultation with EMBC and other end-users and will be reflected in the Service Level Agreements. The acceptance criteria will form the basis for EMBC to formally accept the system at the end of the commissioning.

Data Sharing

During commissioning, other government and non-government organizations might approach ONC with specific seismic data or data product needs. This will be supported on a best effort basis, recognizing that all ONC data are already in the public domain within seconds of their initial acquisition. Implicit in this statement and already committed to is the data exchange with the Pacific Northwest Seismic Network who are getting parametric data from our sensors.

Conversely, on the recommendation of EMBC, ONC might be in a position to consider third party sensor data to be integrated in the EEWS, should the sensor(s) be suitable to effectively and positively contribute to the objectives of the system in the long term. Although such external instrument integration might be feasible, it may require additional time and resources where the impact of added effort will be carefully assessed.

Operational Requirements

As discussed in the previous section, system commissioning is an essential step toward operational competence. ONC intends to use this phase to: develop a comprehensive understanding of critical systems maintenance, support and operational costs; complete system-wide testing and validation; launch meaningful monitoring tools; provide appropriate documentation; develop crucial training materials; plan and mitigate against operational risks; and complete fundamental agreements, that will collectively facilitate successful operations. Furthermore, the costs associated with standard operations will be more clearly understood, and a 5-year operational budget will be determined with a good level of confidence. Lastly, throughout the duration of the commissioning phase, training materials will be developed in concert with a list of important activities, requirements, goals and expectations that will be critical for the operational transition of the EEWS.

Inventory of Current Agreements

Throughout the duration of this project, a number of agreements (Tables 11 through 15) were required to access sites, install equipment, provide power, receive data, utilize contractors and commercial operators, obtain expertise and complete testing.

Table 11. List of Land-Use, Installation Agreements/MOUs

Albert Head	Kwois Creek	Strathcona Park Lodge
Bamfield Marine Sciences Centre	Mount Grey	Survey Mountain
Beaver Cove	Myra Falls	Tofino
Brooks Peninsula	Newcastle Ridge	Ucluelet
Chemainus	Nootka Lighthouse	Vancouver
Eliza Dome	Pacific Geological Centre	Victoria Peak

Albert Head	Kwois Creek	Strathcona Park Lodge
Gold River SD-84	Port Alberni	Village of Port Alice
Holberg	Quadra Island	Woss
Jordan River	Port Hardy	Zeballos Elementary School
Lake Cowichan	Port Renfrew	

Table 12. Utility/Telecommunications Agreements

Name	Type of Utility/Service
Alpine Satcom	iDirect services
BC Hydro/NRCan (Consent to Sublicense)	Hydro power
Bell Mobility	Cell phone service
Intraworks	Network connectivity
Natural Resources Canada	Network/data Partners
Quinsam Communications Ltd.	Wifi
Xplorenet	Satellite communications

Table 13. Service Agreements

Canadian Scientific Submersible Facility	Natural Resources Canada access to Coast Guard Vessels	Pacific Northwest Seismic Network
Driving Force Vehicle Rentals	North American Zone Cable Maintenance Agreement	USGS ShakeAlert (EEW education)
E&B Helicopters	Ocean Exploration Trust (vessel & crew)	West Coast Helicopters

Table 14. EEWS End User Testers Agreements

BC Ferries	Oak Bay Fire Department	Translink
Fortis BC	Pacheedaht First Nation community	Protrans
HEMBC	Pelmorex	

Table 15: Highly Qualified Persons/Consultant/Organizations Agreements

Table 15. Highly Qualified Persons/Consultant/Organizations Agreements

Name	Area of Expertise
Arescon Ltd.	Science consulting services for sensor location and equipment specs
Bob Crosby	System analyst
Meg Patchet	EEW alerting Best Practices and EEW end-user training

Name	Area of Expertise
Ziming Wang	Cost-benefit analysis of EEW in Vancouver Port community

System Testing

Full system testing is the evaluation of a complete and fully integrated operational product, where every element of the system has been assessed for its compliance with specified requirements, both at an individual component basis and on a full system scale. Testing is a critical step in assessing the quality and reliability of the integral components of a system, necessarily conducted on an ongoing basis from project initiation to final product acceptance. Although ONC has developed several levels of testing procedures, a continual and iterative approach will be necessary to identify and understand any gaps that may still exist. The current system testing framework is discussed below with the assumption that more comprehensive and sophisticated procedures will be developed during the commissioning phase. Please refer to section 6.1 for a more detailed description of this approach.

Instrument-based testing requirements and procedures

Following the deployment of an instrument to a field site, steps are undertaken to verify the initial accuracy of the data and metadata during the commissioning phase.

The steps for instrument-based commissioning are documented in the Oceans 2.0 workflow tool. The device workflow tool in Oceans 2.0 can support heterogenous instruments, varying deployment contexts (e.g., networked vs autonomous, seafloor vs land-based) and complex operation logistics (e.g., hundreds of instruments, multi-department and partner involvements). This workflow tool facilitates task management for instruments affected in a given maintenance expedition, ensuring that work is streamlined, traceable and repeatable amongst the various organizational teams involved. Instruments affected by a particular expedition are added to a process group and assigned a relevant process. A summary page for each expedition includes a table listing devices with their processes and most recently completed phase. Once an instrument is assigned a process, a worksheet populates with tasks grouped by phase.

Features include the following:

- Customizable and versioned workflows;
- Web-based Administration Tool and Worksheets;
- Permission-controls;
- Task status updates associated with user;
- Tasks link to further details of execution in JIRA tickets, and more detailed definitions in wiki pages;
- Records events in an instrument or system’s life cycle; and
- Incorporates tasks that enhance FAIR and CoreTrustSeal compliance.

Common tasks involved in instrument-based commissioning involve different teams at ONC teams.

Observatory Systems

This team ensures instrument power and network communications.

Data Stewardship

This team updates site specific metadata, verify data access and searchability, verifies the instrument is correctly connected to topology (the representation of an instrument connection to the ONC infrastructure), and verifies receipt of the data stream.

Data Team

This teams completes the initial evaluation of the data quality and comparisons with historical data, ensures all data products are available through Oceans 2.0, data preview, and third-party sites where applicable (IRIS), adds instrument sensors to earthquake associator for inclusion in EEW event detection.

The tasks described here are generalized and specific details can vary between device types. More detail about the evaluation of data quality are provided in the following section. During the commissioning phase, additional tasks will be added to the workflow as the instrument-based processing steps are refined.

Station-based testing requirements and procedures

After a site has been integrated into the EEWS the data and metadata are examined during the commissioning phase. The station-based commissioning can be separated into two phases: an initial sanity check to verify the data and metadata accuracy from the individual instruments deployed at the site as discussed in the previous section, followed by ongoing monitoring of the data quality and site suitability for the EEWS. The specific procedures for EEW station-based commissioning are still under development. At a high level, the proposed station-based commissioning procedures are: (1) monitoring of overall site health and suitability of the site to the EEWS; (2) accumulating statistics on the site availability and latency; (3) gathering statistics on contributions to EEWS events on a site-by-site basis; and (4) reporting issues with data and data streams and initiating communication with stakeholders.

Considering these procedures, ongoing station-based testing may include analysis of data gaps to identify specific and systematic issues with the data flow from EEW stations related to networking and communication, instrument failure, and power interruptions. Also noise monitoring of accelerometer data is needed to establish the noise floor of the site, examine seasonal and other natural variability, and identify anthropogenic sources of noise that may impact earthquake detection. Additionally, site-by-site optimization of the EEW parameters used by Titan and tiltmeter middleware is needed to improve earthquake detection. These include the short-term average (STA) and long-term average (LTA) filter window sizes as well as the P- and S-wave detection thresholds. Station-based testing also includes monitoring of accelerometer P- and S-wave detection frequency and health and noise monitoring of geodetic (Precise Point Positioning) data to track statistics for position error, number of satellites used, number of satellites rejected - for land-based stations. There is also a need for periodic adjustment of a-priori position estimates for the geodetic Precise Point Positioning solutions for land-based stations and management of EEW station inputs to the EEW event definition (i.e. adding and removing stations data to the event detection algorithm) Station-based commissioning and testing would benefit from the development of automated tools for monitoring site-specific statistics described above.

Some of the specific station-based procedures above are currently captured and documented in the Oceans 2.0 workflow tool. The workflow tool can be expanded to include more of these procedures as they are refined during the commissioning phase.

Software-based testing requirements and procedures

A complete and integrated software test is required to evaluate and verify a system's overall compliance with specified requirements. Unit tests can be used to assess individual algorithms (classes), where the addition of new classes (and their methods) must be validated by introducing new corresponding unit tests. If any method in a currently operational class are varied, relevant unit tests require appropriate updates to ensure the output of a method is never unintentionally changed. At any point when ONC updates software code, all of the relevant unit tests are automatically run. In the event a unit test fails, the code changes will not be merged into the master branch until accurately corrected.

As mentioned previously ONC uses a QA environment, which is an offline duplicate of the operational environment, to test various aspects of the network and data flow. This enables ongoing simulations, where results can be checked manually to verify the appropriate and accurate processing of data.

Exploring beyond the confines of simulation software, ONC has set-up a testing station that continually runs accelerometer and GNSS equipment that are fed directly into the QA system for ongoing testing purposes. The messages are evaluated to ensure correct processing according to the following requirements: (1) messages never backup in the ActiveMQ message broker on any of the JVMs; (2) raw data and sensor readings are archived seamlessly without any gaps in data; (3) GNSS displacements fall around 10 cm, peak displacement and peak ground displacement do not report data values, peak displacement error and peak ground displacement error always report their floor values; and (4) all messages are sent to both associator instances.

Lastly, to test the event detection code a set of real and simulated earthquake data is used. The earthquake data is fed through the associator and evaluated for the number of event detections, the location of all epicentres, the origin times, and the event magnitudes. These earthquake data sets are always run automatically through new code changes to determine if the updates contain hidden bugs or other issues. In the event new code changes render a diminished detection, the modified code will not be merged with existing master branches until all necessary corrections have been applied and verified.

Before any code is released into the operational production database, it is subject to rigorous manual regression testing. These regression tests involve verifying the data flow on both simulated and real instruments in the QA environment, no data gaps are present, and events can be detected. An instance of the client software is also run to confirm that it both receives and responds to incoming test notifications. Lastly, startup cache loading is assessed and verified that successful reloads occur without a connection to the database.

Data quality testing and validation requirements and procedures

Aspects of data quality testing and validation are addressed in other sections of this report including the Instrument-based, Station-based, and EEW Integrated System Testing sections. Results from this testing will inform the service level agreements and operational requirements beyond the commissioning phase.

EEW Integrated System Testing and Analysis

This section describes proposed testing and validation of the EEW integrated system.

Examples of the tests, validation, and monitoring procedures of the integrated EEW system to be developed, considered, or implemented during the commissioning phase may include status tests, system performance analyses, failure analyses, simulated tests, and analyses of events. Daily system health/status tests include a comprehensive, graphical system status dashboard with displays of data, metadata, and metrics to allow operators to quickly identify and diagnose issues; and automated generation of a daily system status report or messages. Analysis of system performance identify bottlenecks in data flow and alerting, further explore bandwidth constraints and limits, and mitigate impact of flooding the system with data after communications with stations are reestablished. Failure analyses will test EEW system event detection performance with simulated station failures to: identify critical stations/regions in the EEW network of stations and to identify geographical regions that may require additional site coverage and redundancy; determine the impact of randomized individual station outages caused by instrument failures, network and communication issues, power failure; and determine the impact of area-wide outages affecting multiple sites. Plausible failure scenarios may include the loss of network connectivity to a region, extreme weather and wildfire events, or earthquake damage. Testing with pre-recorded and simulated data takes place before any significant software changes are made and at regular intervals. Ongoing analysis of events comprises a review of real earthquake events to examine station contributions, event association times, and time to notification; identify and screen spurious false-positive detections and teleseismic events; and the generation of automated event reports.

And validation of the overall EEW integrated system performance should be conducted in consultation with external subject matter experts and end users and be included in the peer review process.

Summary

Ocean Networks Canada, with the assistance of its Natural Resources Canada and Pacific Northwest Seismic Network partners, has assembled a system whose architecture comprises seismic and geodetic sensor networks and complex power, communication and computer systems. Now with the foundational elements in place, a commissioning phase will verify and validate it. System commissioning is an important step in delivering a critical and complex technical system to its future users. Once completed, the integrated EEWS network will be capable of delivering notification of seismic events occurring on the Cascadia subduction zone to southwestern BC stakeholders, and where possible, other crustal and deep intra-slab events occurring within the geographic range of the network. ONC is confident that this comprehensive warning system will provide the means for early detection and notification tools for public safety.

Acknowledgments

Ocean Networks Canada acknowledges the following entities that have made this EEW system possible: Emergency Management BC for providing the leadership and the wherewithal to carry out the project; Natural Resources Canada who provided access to some of their seismic sites and instruments, as well as staff, support and GNSS software and overall advice; the Pacific Northwest Seismic Network who are making extracted parameters from their large Washington and Oregon EEW network available for integration in the associator; the various beta-testers such as ProTrans, SNC-Lavalin, the Pacheedaht First Nation, and the Oak Bay fire department, to cite just a few, with whom we have signed agreements and who have demonstrated a strong interest in receiving earthquake early warnings in the future; private landowners and First Nations, who have allowed us to install equipment on their premises; BC Parks, BC Forests, the Ministry of Transport and Infrastructure and Front Counter BC who have supported and expedited land leases; the Canadian Coast Guard who have contributed their stations, helicopters and vessels; the Ocean Exploration Trust for their vessels and remotely operated underwater vehicle; the University of Victoria for legal services; Shared Services Canada for the network security reviews; various municipal authorities such as the Capital Regional District , Port Hardy and Greater Vancouver Regional District have provided support to allow us to work in their jurisdiction; the Department of National Defence that supported the creation of secure codes to extract parameters from seismic devices; and finally Public Safety Canada and Defence Research and Development Canada who, through their Canadian Safety and Security Program, contributed funds to support ONC as we were building the system.

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Appendix A: Analysis of the First Major Earthquake Detection

Summary of the Event

On October 21, 2018, a series of three >M6 earthquakes occurred in the offshore area along the Sovanco Fault zone on the Explorer Plate. These, predominantly strike-slip events, occurred within 45 minutes of each other and did not result in a tsunami. While this type of earthquake series is not uncommon, these events, and the data gathered from them, offer insight into the fault mechanics and tectonic activity in the region.

These events were also an excellent live test case for ONC's EEW system that was under development at the time of the earthquakes. This report will focus on the first of these three events, a 6.5Mw earthquake that occurred 218 kilometres southwest of Port Hardy at 22:39:30 PDT.

Local Time:	22:39:30 PDT
Magnitude:	6.5 Mw
Latitude:	49.2 North
Longitude:	129.7 West
Depth:	10. km
UT Date and Time:	2018/10/22 05:39:30 UT

Did you feel it?

Fill out our questionnaire.

Approximate Location of Earthquake: There are no reports of damage, and none would be expected. No tsunami expected. No reports of this earthquake being felt.

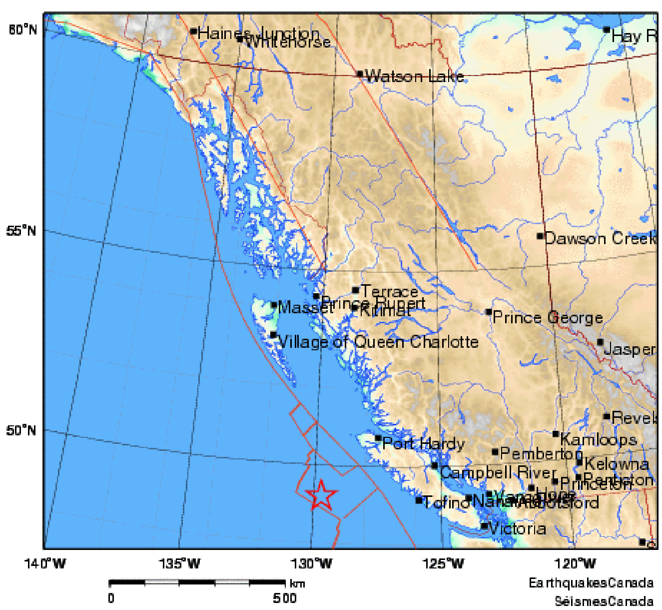

Figure 8. Oct 21, 2018 22:39:30 PDT Earthquake report from Natural Resources Canada.

At the time of the earthquake, Ocean Networks Canada (ONC) was in the process of developing an earthquake early warning system (EEWS) capable of detecting, analyzing and delivering notifications to End-users in southwestern BC for earthquakes originating from the Cascadia Subduction Zone (CSZ). While this event was to the west of the CSZ, it does provide a valuable test case for the EEWS. Live events allow for systems tests that are outside of a controlled context. They provide real-time information that test system performance, operational status and illustrate priorities for system improvements.

This event was detected by a total of 16 offshore and land-based seismic sensors that were operating and reporting data to the central associator at the time. This was the first earthquake of sufficient size to be detected and met the minimum criteria to send earthquake notifications to End-users. It was a successful test of the EEWS and illustrated the performance of the system that was in place.

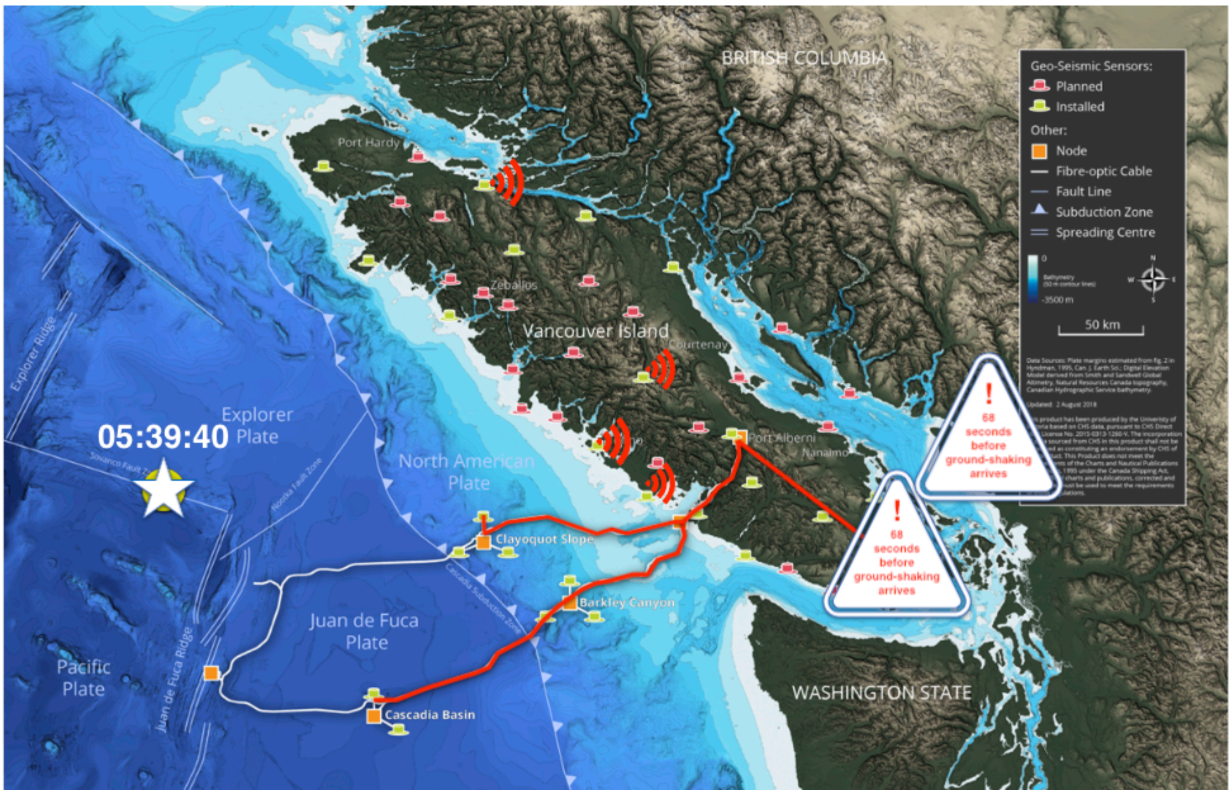

Figure 9: ONC's EEW system as of October 21, 2018, illustrating the sensor locations that initially detected and analyzed the p-wave and made earthquake notification estimations.

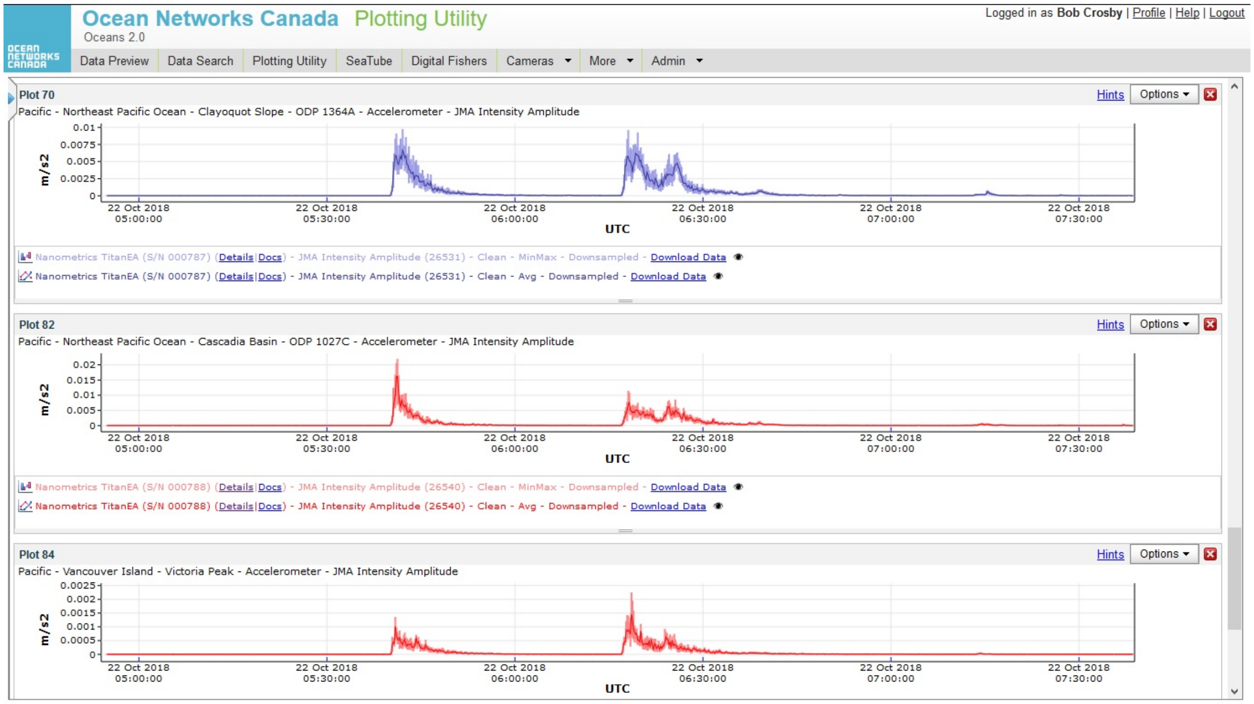

Figure 10: Example of sensor plots from three of ONC's offshore and land-based seismic sensors, as view through ONC's Oceans 2.0 data management system.

Timeline

At 22:40:24 seven ONC sensors detected the p-waves derived the essential parameters such as time and peak displacement amplitude and sent it to the ONC associator in Victoria that confirmed an earthquake was underway. At that time, an earthquake notification was sent to, and received by, End-users with the following results:

Magnitude estimate - 6.6 Mw
Location - 48.9 N, -129.4 W
Earthquake Origin Time – 22:39:43 PD

Here is the official (and seismologist reviewed) earthquake information given by Natural Resources Canada (NRCan) after the event:

Magnitude – 6.5 Mw
Location – 49.2 N, -129.7 W

Earthquake Origin Time – 22:39:30 PDT

Source: http://www.earthquakescanada.nrcan.gc.ca/recent/2018/20181022.0539/index-en.php

The magnitude, location and time estimations made in the initial earthquake assessment by the EEWS are considered very accurate when compared to the official earthquake details.

Magnitude Error - 0.1 Mw
Location Error – 28 kilometers
Earthquake Origin Time Error – 13 seconds

As the event progressed and more sensors detected the earthquake, 13 subsequent notifications were sent to End-users with updated event information. Magnitude estimations fluctuated slightly during the event sequence from 6.2 Mw – 6.8 Mw but generally showed good correlation to the final magnitude. The errors in Location and Earthquake Origin Time stayed consistent throughout the event.

Errors in estimations are based on the final earthquake event report by Natural Resources Canada which differ slightly to the event report by the USGS which can be reviewed here: https://earthquake.usgs.gov/earthquakes/eventpage/us1000hfgn/executive

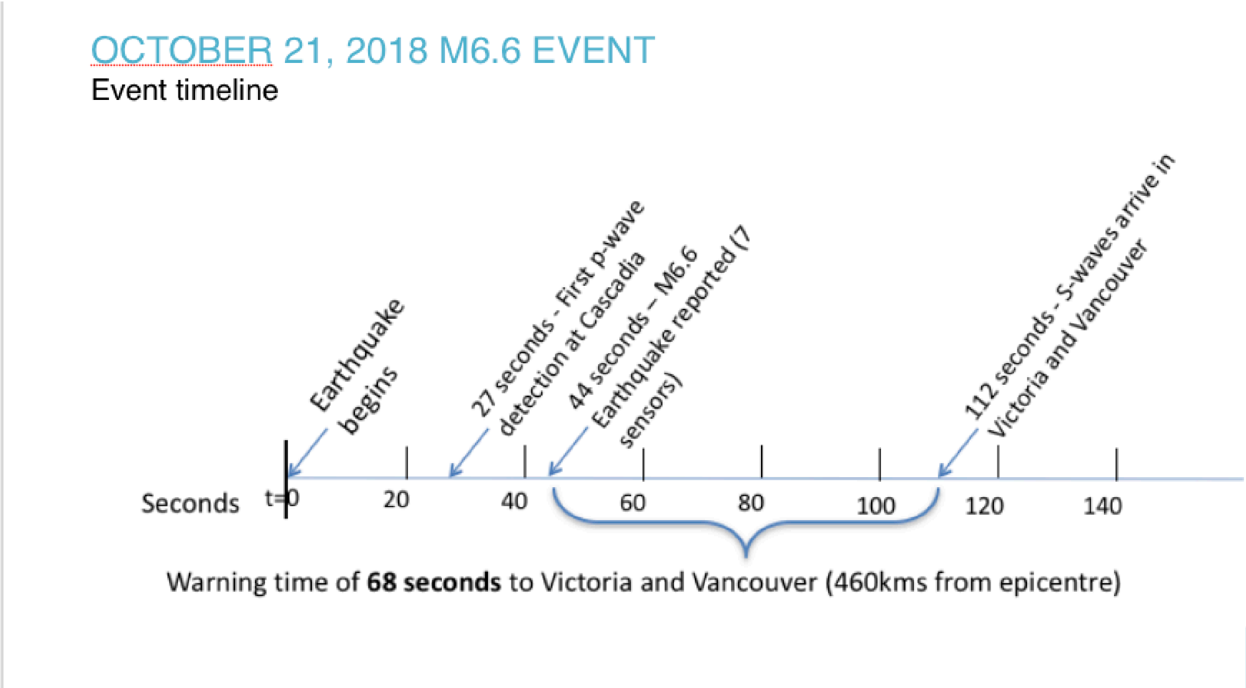

Figure 11 – Timeline of the earthquake event as it unfolded and was detected and analyzed by the ONC EEW system..

End-User Notifications

At the time of the event, there were three End-users set up to receive EEW notifications, namely, Fortis BC, The District of Oak Bay and Protrans. Protrans, which operates the Canada Line light rail system were the most advanced in the use of EEW notifications. As a 'ground-truth' measure, ONC installed a seismic sensor at the Canada Line Operations and Maintenance Centre in Richmond, which was in operation at the time of the earthquake event.

Protrans received a "test" earthquake notification for the event at 22:40:24, 44 seconds after the official earthquake origin time and 68 seconds before the ground shaking was observed at the on-sight sensor. This test notification was sent via email to Protrans that related that this event was below the threshold of a felt earthquake. If this event had been of large enough magnitude, Protrans would have received 68 seconds of advanced notice prior to the onset of ground shaking.

Lessons Learned

This detection of this first significant event, and occurring shortly after a number of sensors had just been configured to communicate their parameters to the event associator, was very encouraging as it provided good early confidence in the capabilities of the system. It delivered precise epicentre coordinates and demonstrated a good handle on the magnitude. Other subsequently observed events allowed us to continue to refine the system and to best take advantage of data from the GNSS receivers, determine heuristics to eliminate false positives (an issue that also affects other EEWS) and improve on the overall performance/ speed of the system.

For the record, we want to repeat this set of limitations and specifics of an earthquake early warning system:

- EEW systems do not predict earthquakes, they measure earthquake-triggered ground accelerations after the initiation of the event
- Sensors detect and analyze the first few moments of acceleration data from the first waves (p-waves) that radiate from the earthquake hypocentre
- As the earthquake unfolds over time, more sensors the original p-wave and the system updates the calculations
- There is an inverse relationship between the accuracy of an event detection and speed of its notification, meaning the sooner one wants to send the notification, the poorer the accuracy
- A minimum of four sensors are required to detect p-waves prior to be able to determine the epicentre and magnitude of an event
- Once a notification is sent, the recipient will calculate the approximate shaking intensity at their location based on earthquake parameters combined with ground motion prediction equations that do not account for soil/building conditions or other variables that can influence the intensity of shaking at specific locations

Appendix B: Inventory List of Physical System Assets at Each Land-Based Site

Table 16. Inventory

Site	Server	Cell modem	Router	Power Manager	Seismic Sensor	GNSS Sensor	Small Battery	Large Battery	AC Charger	Solar Charger	Solar Panel	Wire-less Radio
Albert Head	1	0	1	1	1	0	2	0	1	0	0	0
Bamfield	1	0	1	1	1	0	4	0	0	0	0	0
Beaver Cove	1	0	1	1	1	0	0	1	0	0	0	0
Brooks Penins.	1	1	1	0	0	0	0	2	0	0	0	1
Chemainus	1	0	1	1	1	0	0	1	0	0	0	0
Cumberland	0	0	0	0	0	0	0	0	0	0	0	0
Eliza Dome	1	0	1	1	0	0	0	4	0	1	3	0
Fair Harbour	0	0	0	0	0	0	0	0	0	0	0	0
Gold River	1	0	1	1	1	0	0	0	0	0	0	0
Holberg (instrument site)	1	0	1	0	0	0	0	0	0	0	0	0
Jordan River	1	0	1	1	1	0	0	1	0	0	3	0
Kwois Creek	0	0	0	0	0	0	0	0	0	0	0	0
Lake Cowichan	1	0	1	0	0	0	0	0	0	0	0	0
Maynard	0	0	0	0	0	0	0	0	0	0	0	0
Mt. Grey	1	0	1	0	0	0	0	0	0	0	0	0
Myra Falls	1	0	1	1	1	0	0	0	0	1	4	0
Nanoose	0	0	0	0	0	0	0	0	0	0	0	0
Newcastle Ridge (Sayward)	1	0	0	0	0	0	0	0	0	0	0	0
Nootka Lighthouse	1	0	1	1	0	0	2	0	0	0	0	0
Port Alice	1	1	0	1	1	1	4	0	1	0	0	0
Port Hardy	0	0	0	0	0	0	0	0	0	0	0	0
Port Renfrew	1	0	1	0	0	0	0	0	0	0	0	0
Pt. Alberni	1	0	1	1	1	0	0	2	1	0	0	0
Quadra Isl.	1	0	1	1	1	0	0	1	0	0	0	0
Secret Beach	0	0	0	0	0	0	0	0	0	0	0	0

Sharp Point	0	0	0	0	0	0	0	0	0	0	0	0
Sidney Pacific Geoscience Centre	1	1	0	1	1	0	2	0	0	0	0	0
Strathcona Park	1	0	1	1	1	1	4	0	1	0	0	0
Survey Mt.	1	0	0	0	0	0	0	0	0	0	0	0
Tahsis	0	0	0	0	0	0	0	0	0	0	0	0
Taylor River	0	0	0	0	0	0	0	0	0	0	0	0
Tofino	1	0	1	1	1	0	0	0	0	0	0	0
Ucluelet	1	0	1	1	1	0	2	0	0	0	0	0
Vancouver (Protrans)	0	0	0	0	1	0	0	0	0	0	0	0
Victoria Peak	1	1	0	1	1	1	0	4	0	1	3	0
Woss	1	0	0	0	0	0	0	0	0	0	0	0
Zeballos	1	0	1	1	1	0	2	0	1	0	0	0

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Ocean Networks Canada (ONC) has developed an earthquake early warning system for southwestern British Columbia that leverages existing submarine sensor networks, its world-renowned capabilities to install instrument networks both on- and off-shore, and a data handling reputation for managing and processing important data volumes. Furthermore, extensive efforts have supported the integration of neighbouring seismic networks to enhance local detection capabilities, expand the system footprint, and promote operational collaborations. As the development is now virtually complete, ONC is preparing for the next important phase: a system-wide commissioning. This phase will reveal any system gaps, determine the acceptance criteria, understand and optimize operational costs by adding redundancy in key areas, and qualify the actual system's capabilities. This report will both summarize what was accomplished and articulate the objectives of the commissioning phase of the Cascadia Earthquake Early Warning System (EEWS).

Ocean Networks Canada (ONC) a élaboré un système d'alerte sismique précoce pour le sud-ouest de la Colombie-Britannique qui exploite les réseaux existants de capteurs sous-marins, ses propres capacités de renommée mondiale en installation côtière et extracôtière et sa réputation en traitement des données afin de gérer et de traiter de grands volumes de données. De plus, nous avons déployé d'importants efforts pour intégrer les réseaux sismiques voisins afin d'améliorer la détection locale, d'élargir la portée du système et de favoriser les collaborations opérationnelles. L'étape d'élaboration étant presque complète, ONC se prépare à la prochaine grande étape : la mise en service intégrale du système. Cette étape permettra de détecter les lacunes du système, le cas échéant, d'établir les critères d'acceptation, de comprendre et d'optimiser les coûts opérationnels en ajoutant une redondance dans des aspects clés et de déterminer les capacités réelles du système. Le présent rapport résume les réalisations et énonce les objectifs de l'étape de mise en service du système d'alerte sismique précoce (EEWS) Cascadia.